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AN OBSERVATIONAL ANALYSIS OF TROPICAL CYCLONE RECURVATURE

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by Stephen J. Hodanish

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AN OBSERVATIONAL ANALYSIS OF TROPICAL CYCLONE RECURVATURE

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ABSTRACT

Twenty-one years (1957-77) of North Pacific rawinsonde data are used to show how the large scale synoptic pattern interacts with the tropical cyclones' environment just prior to, and during the recurvature process. This study is believed to be the first to quantitatively examine how the environmental wind fields at all levels of the troposphere are related to tropical cyclone motion prior to, and during, recurvature. Significant changes in the upper tropospheric zonal wind fields were found to the north and northwest of tropical cyclones one to two days prior to beginning recurvature. These cyclones actually began to recurve when positive zonal winds penetrated into the mid and upper troposphere, 6° from the cyclones' center. Tropical cyclones which did not recurve showed negative zonal winds at this radius.

Based on the results of this study, a recurvature forecasting scheme was developed using the environmental windfields measured in the northwest region of the cyclone. This recurvature scheme was then tested on 55 tropical cyclones which developed in the northwest Pacific in 1984-86. It was found that tropical cyclone direction related fairly well to the mid and upper tropospheric windfields to the north, northwest and west of the cyclone. This recurvature scheme was then used in real-time during the Tropical Cyclone Motion (TCM-90) experiment which was conducted during the summer of 1990 in the Northwest Pacific. This scheme was found to be generally successful.

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LIST OF SYMBOLS AND ACRONYMS

LIST OF ACRONYMS

BMRC = (Australian) Bureau of Meteorology Research Centre

CSU = Colorado State University

EOF = Empirical Orthogonal Function

JTWC = Joint Typhoon Warning Center

L = Left turning cyclones

L Point = The location where a left turning cyclone first begins resuming a west–northwest course (cyclone direction $< 320°$)

mb = millibar

ms^{-1} = meter per second

N = North

NR = Non-recurving cyclones

NW = Northwest

NNW = North–Northwest

OCT = Octant

R = Sharply recurving cyclones

R Point = The location where a recurving cyclone first begins to deviate from its previous west–northwest course

RECNUM = Recurvature number

SR = Slowly recurving cyclones

TC = Tropical Cyclone

TUTT = Tropical Upper Tropospheric Trough

W = West

WNW = West–Northwest

Chapter 1

INTRODUCTION

Forecasting tropical cyclone recurvature is one of the leading problems for hurricane/typhoon centers worldwide. Tropical cyclones which are forecast to track on a westerly course, but then recurve, typically lead to large forecast errors and less confidence in subsequent forecasts. It has been shown that 72-h track forecast errors as great as 1850 km occur nearly every year in the Northwest Pacific (Sandgathe, 1987). A more serious dilemma for the forecast centers occurs when a cyclone which might recurve is approaching a large metropolitan area. If a landfall forecast is made but the cyclone recurves, millions of dollars are lost in unnecessary preparation and lost time at work. It is estimated the cost of preparing a 450 km stretch of U.S. Gulf Coast for a hurricane to be 50 million dollars (Sheets, 1990). Likewise, if the cyclone is predicted to recurve away from the coast, but does not, the cost can be much larger, both in lives and dollars. In either case, incorrect forecasts cause the public to have less confidence in forecast warnings the next time a cyclone threatens the area. Although a considerable amount of research has been done on tropical cyclone motion (see, for example Chan, (1984); Holland, (1984); Pike, (1985); Elsberry et al., (1988); and others) very little research has been accomplished with respect to the specific environmental wind conditions which distinguish recurvature from non-recurvature.

1.1 Previous Studies Related Specifically to the Recurvature Forecasting Problem

The first study to relate the large scale synoptic environment to tropical cyclone recurvature was done by Riehl and Shafer (1944). They showed recurvature was not likely to occur until the base of the mid latitude westerlies, located west of the cyclone, reached the latitude at which the cyclone was located. Observations also showed that not all troughs approaching a cyclone caused recurvature. Mid- latitude troughs in the westerlies may interact with the cyclones circulation to cause the cyclone to slow down, or even turn to the right, but as this synoptic feature by-passed to the north, the cyclone resumed a west-northwest course.

During the next 16 years, a considerable amount of research was conducted on tropical cyclone motion. Since it was shown that tropical cyclones responded to the environment in which they were embedded, most of the research during the early part of this period was based on the "steering" concept. As high speed computers became available, statistical, climatological and numerical studies were employed to help forecast the motion of tropical cyclones. Although this work helped explain, to a limited extent, why tropical cyclones move as they do, none of the studies dealt explicitly with the recurvature problem. In the early 1960's Dunn and Miller (1960) documented three general synoptic conditions which were favorable for tropical cyclone recurvature. These included:

1. High amplitude troughs extending from the westerlies;
2. Low latitude troughs building into the westerlies; and
3. Weakness in the subtropical ridge.

The first study which analyzed how environmental wind fields changed prior to recurvature was conducted by George and Gray (1976b). They compared and contrasted the 200 and 700 mb wind, height and temperature fields of recurving and non-recurving cyclones. In the study, 21 recurving cyclone tracks were paired to 21 non-recurving cyclone tracks. The cyclones were defined to be a pair if the separation point of the recurving cyclone was within 5 ° latitude of the non-recurving cyclone track (the separation or S-point was arbitrarily defined at the longitude where the recurving storm track begins to deviate significantly from the non-recurving track). The paired tropical cyclone tracks were divided into 3 consecutive 24 hour time periods prior to the S-point. These time periods will be referred to as S-12, S-36 and S-60. Their study focused primarily on the environment 8 to 20 ° from the cyclones' center since it was believed that large scale synoptic patterns favorable to recurvature would likely be seen at these radii one to three days prior to beginning recurvature. The primary result of their study showed that 200 mb wind fields were significantly stronger from the west for recurving cyclones than those of the non-recurving cyclones. A more important result, though not explicitly shown, was that wind fields of the pre-recurving cyclones tended to increase in magnitude as the cyclone approached the separation point. As shown in Table 1.1, 200 mb zonal wind differences between pre-recurving time periods tend to be quite large, especially at outer radii.

Table 1.1: Zonal 200 mb wind fields (top) and wind field differences (bottom) from George and Gray's pre-recurving S-12, S-36, and S-60 cyclone time period stratifications. Units in ms^{-1}.

Radius From TC Center	Zonal Winds West of Cyclone			Zonal Winds Northwest of Cyclone			Zonal Winds North of Cyclone		
	S-12	S-36	S-60	S-12	S-36	S-60	S-12	S-36	S-60
20°	12	-1	-3	57	41	36	55	42	34
18°	2	-7	-5	37	34	29	45	41	39
16°	-3	-3	-3	35	27	22	39	31	28
14°	-9	-7	-3	37	23	16	31	28	19
12°	-5	-6	-6	20	17	15	26	22	21
10°	-2	-7	-4	17	13	9	16	12	15
8°	-3	-8	-6	9	6	2	12	-4	0

	Zonal Wind Difference West of Cyclone	Zonal Wind Difference Northwest of Cyclone	Zonal Wind Difference North of Cyclone
	(S-12) minus (S-60)	(S-12) minus (S-60)	(S-12) minus (S-60)
20°	15	21	21
18°	7	8	6
16°	0	13	11
14°	-6	21	12
12°	1	5	5
10°	2	8	1
8°	3	7	12

To see if 200 mb wind fields [from George and Gray's (1976b) study] have value for predicting recurvature in real time, Guard (1977) compared actual 200 mb wind fields of cyclones which might recurve to the 200 mb S-12, S-36 and S-60 wind fields. This test was conducted at the Joint Typhoon Warning Center (JTWC) during the 1974-76 Northwest Pacific typhoon season. Guard noted that two corrections were necessary before comparisons could be made between the S-12, S-36 and S-60 wind fields of the actual 200 mb wind fields for the cyclones in question. The first correction was to designate the recurvature point. In an operational basis, the point where the cyclone first takes on an eastward component of motion is more significant then the separation point. Typically, this required a -24 hour adjustment of the S-12, S-36 and S-60 200 mb wind fields. The second correction relates to seasonal environmental differences of winter versus summer recurving cyclones. The upper tropospheric outflow of "winter regime" recurving cyclone was found to have a direct link with the westerlies 72 hours prior to recurvature whereas "summer regime" recurving cyclones did not show this link until 24 to 36 hours prior to recurvature.

In the three years during which Guard conducted his test, 28 of a total of 49 tropical cyclones recurved. Although all 28 storms which recurved were successfully predicted using George and Grays' 200 mb wind regime, the procedure also forecasted recurvature for 9 other storms which did not recurve; hence George and Gray's 200 mb wind regime overpredicted recurvature by a factor of about 25% which is not a significant improvement over existing forecast methods which were then employed at JTWC.

Two possible drawbacks to George and Grays' (1976b) recurvature study were: 1) Only wind fields at two tropospheric levels were analyzed and 2) Only data from 8 to 20° latitude from the cyclones center were analyzed. It is believed that these drawbacks account for the 200 mb wind fields overpredicting recurvature in Guard's study. As will be shown in Chapter 3, upper tropospheric westerly winds at large radii show the largest changes prior to recurvature. However, tropical cyclone recurvature was not found to be dependent on the speed of positive zonal winds at radii extending past 9°. Rather, tropical cyclone recurvature was found to be dependent on how close to the cyclone's center positive zonal winds in the mid and upper troposphere penetrated.

Additional recurvature studies by Leftwich (1979) and Lage (1982) incorporated statistical techniques to predict recurvature. Leftwich used cyclone position, motion, intensity and 1000-100 mb geopotential height predictors to forecast the probability of recurvature for Atlantic tropical cyclones. The results of his statistical model did not out-perform climatology. Lage used Empirical Orthogonal Function (EOF) representations of 500 mb geopotential height fields plus persistence related variables to predict recurvature or non-recurvature at various time intervals in the northwest Pacific. The combination of both methods consistently outperformed climatology at all forecast times intervals.

Ford (1990) also analyzed changes in the environment surrounding pre-recurving cyclones as the cyclones approached recurvature (cyclone direction > 000° east of north). EOFs were calculated for distinguishing 700, 400 and 250 mb vorticity fields to see if they have value for distinguishing recurvers from non-recurvers, and, when a cyclone was identified as a possible recurver, to estimate time until recurvature. It was shown that the first six EOF coefficients of the upper tropospheric (250 mb) vorticity field were useful for distinguishing recurvers from non-recurvers but skill for predicting when recurvature would occur was low.

Although predicting recurvature in itself is difficult, predicting if the cyclone is going to accelerate into the westerlies is also a major concern for the cyclone forecast centers. Burroughs and Brand (1972) analyzed how surrounding synoptic patterns and cyclone characteristics related to cyclone speed after recurvature in the northwest Pacific. Their results showed that speed of movement 36 hours after recurvature was dependent on time of year, 700 mb synoptic pattern, and meteorological characteristics of the cyclone both during and 24 hours prior to recurvature. Huntley (1981), in an effort to forecast rapid acceleration of tropical cyclones, tried to relate cyclone speed after recurvature to a first order differential equation of motion. Forecasts based on this equation were found to be no better then the official forecast issued by the JTWC. Bao and Sadler (1982) analyzed how mid and upper tropospheric winds on the cyclone's poleward side related to cyclone speed after recurvature. They found a high correlation between the speed of post-recurving cyclones and 500 and 200 mb wind speeds during and 12 hours prior to recurvature. Weir (1982) analyzed how 200 mb synoptic flow patterns poleward of the cyclone related to the acceleration of northward moving cyclones in the northwest Pacific. He found the speed of motion of recurving (or nearly recurving) cyclones tended to be dependent on the speed and direction of the 200 mb winds north through west of the cyclone. He also showed that other meteorological factors, such as strong low level steering currents or tropical upper tropospheric troughs could also alter the speed of north and northeast moving cyclones.

1.2 Summary and Objectives

It is apparent from the above discussion that a comparatively small portion of research on tropical cyclone motion has been directed to specific problems of recurvature. Nonetheless, this research has shown recurvature is primarily caused by either mid latitude westerlies penetrating into the tropics or by a weakness developing in the sub-tropical ridge. In addition, post recurvature studies have shown that upper tropospheric wind fields on the poleward side of cyclones played a significant role in determining cyclone speed after recurvature. When the results of these post-recurvature studies were employed in real-time forecasting situations, they were found to be not too successful. The poor rate of success was likely due to two causes: 1) The lack of sufficient upper tropospheric data and 2) The 200 mb flow field was assumed to be representative of the wind fields below. It was also shown by George and Gray (1976b) that upper tropospheric westerly winds poleward and westward of the cyclone were a precursor to recurvature. However, as shown by Guard (1977), not all cyclones which had strong westerly 200 mb wind flow at these locations recurved.

In general, it appears that although upper tropospheric westerlies are a prerequisite for recurvature, they do not seem to be the cause of recurvature. Clearly a quantitative study is needed on how synoptic scale wind fields throughout the troposphere interact with the deep cyclonic circulation of tropical cyclones prior to and during recurvature. Fundamental questions related to recurvature which need to be addressed are:

- How deep do these westerlies need to be, and how close do they need to get to the cyclone's center, before the cyclone actually begins recurving?
- Do the environmental wind fields surrounding recurving cyclones change significantly prior to recurvature?
- It was shown in George and Gray's (1976b) that the 200 mb winds poleward and westward of cyclones which recurved changed significantly prior to recurvature; do other changes in the wind fields at other pressure levels closer to the cyclone need to occur before the cyclone recurves?
- How do the environmental wind fields of pre-recurving cyclones differ from cyclones which move west-northwest throughout their lifetimes?
- Are there environmental characteristics which can forewarn that a recurvature event will occur?
- How do environmental wind fields of cyclones which recurve sharply differ from those for cyclones which gradually turn to the right and have long northerly tracks before recurving to the northeast?
- Do the environmental wind fields prior to recurvature of sharply recurving cyclones differ from those for slowly recurving cyclones?

The following study was designed to answer these questions by observing how the wind fields throughout the troposphere, extending from 3 to 15° from the cyclone's center, change with time as the cyclones move west, north and finally northeast. Environmental characteristics which differentiate recurving cyclones (prior to recurvature) from non-recurving cyclones are also documented.

Chapter 2

METHODOLOGY AND DATA STRATIFICATION

2.1 Composite Analysis

To document environmental wind fields associated with the recurvature of tropical cyclones[1] 21 years (1957-77) of northwest Pacific rawinsonde data has been analyzed (Fig. 2.1). Rawinsonde data was utilized to study recurvature for the following reasons: 1) rawinsondes provide for data at all levels of the troposphere and lower stratosphere. As was discussed in Chapter 1, many recurvature and post recurvature studies analyzed only one or two levels of the troposphere. Rawinsonde data allows for detailed analyses of wind fields at all levels of the troposphere. 2) The rawinsonde data are actual data which was measured relative to the cyclone. Unlike studies based on smoothed or interpolated wind analysis fields from computer models, rawinsonde data represent the actual winds occurring at that time. In addition, rawinsonde data avoids the "bogus vortex" problem inherent in computer models. 3) The rawinsonde data has advantages over other types of data gathering platforms such as aircraft and satellites. Research/reconnaissance aircraft typically record data at one level of the atmosphere and only near (0–4°) the cyclone's center (Weatherford and Gray 1988a). Although virtually unlimited in areal coverage, satellites can only indirectly measure tropical and subtropical wind fields at two levels (~200 and ~950 mb) and only with confidence when clouds are present.

Unfortunately, tropical cyclones, especially recurving tropical cyclones, spend the majority of their lifetimes over data sparse ocean areas. For this reason, rawinsonde data

[1]Tropical cyclone in this paper refers to any warm core cyclonically rotating storm system with wind speeds sustained at 17 ms^{-1} or greater.

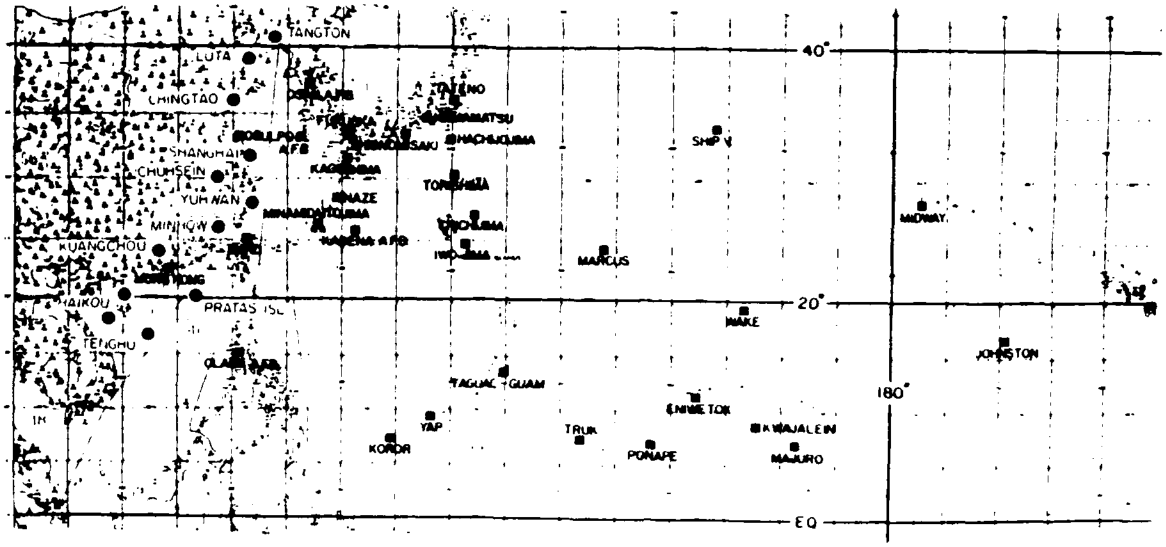


Figure 2.1: Locations of the 42 northwest Pacific rawinsonde stations used in this study.

must be composited. A thorough description of the rawinsonde compositing techniques used in this study is given by Williams and Gray (1973), Ruprecht and Gray (1974) and in several other Colorado State University tropical cyclone motion papers. Simply stated here, there are typically too few rawinsonde stations in proximity of cyclones to allow for detailed analyses of environmental flow fields surrounding individual cyclones. By compositing data for many tropical cyclones with similar characteristics, many of the data limitations can be avoided.

Data from the rawinsonde compositing technique are displayed on a 15 degree circular radius grid which consists of octants of 45 degree tangential extent (see Fig. 2.2). The grid consists of 8 radial bands extending from 0-1, 1-3, 3-5, 5-7, 7-9, 9-11, 11-13 and 13-15 degrees from the TC center. In this study, the wind fields extending from 3-5° through 13-15° in octant 1 (north), octant 2 (northwest) and octant 3 (west) for the following pressure levels, 800, 750. 700, 600, 500, 400, 350, 300, 250, 200, 175, 150, 125, 100, 80, 70, 60 and 50 millibars are analyzed.

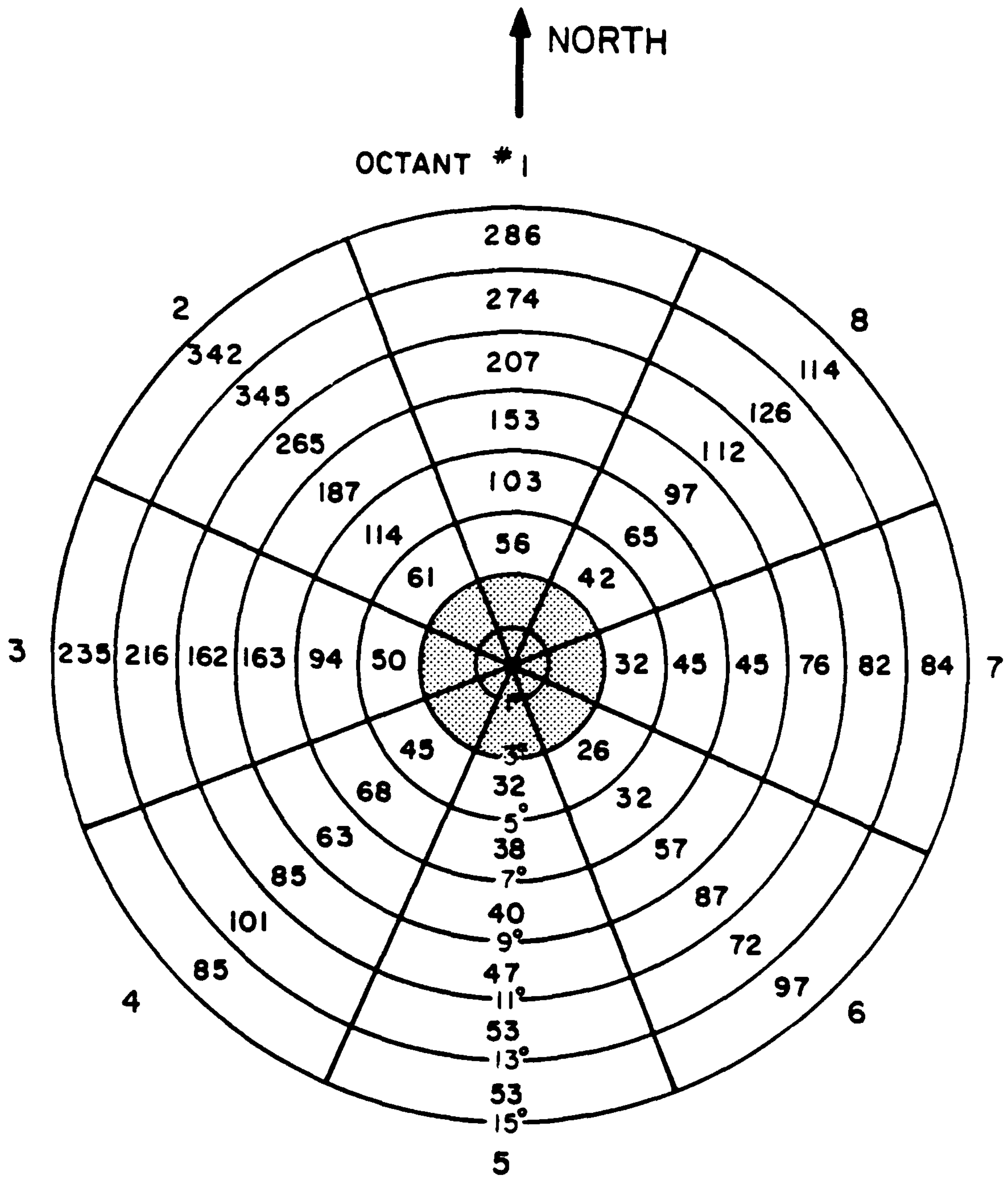


Figure 2.2: Grid used for compositing rawinsonde data. The numbers inside each radial belt represent the number of rawinsonde observations for the sharply recurving cyclone data set (the cyclone data sets will be defined in section 2.2).

2.2 Cyclone Track Stratifications

This recurvature study analyzes four types of cyclone tracks: sharply recurving cyclones, slowly recurving cyclones, left turning cyclones and non-recurving cyclones (see Fig. 2.3). The reason for dividing the recurving cyclones into two categories is that the large scale environment which causes a west-northwest moving cyclone to abruptly turn to the right (sharp recurvers) is likely to be quite different from that for a west-northwest moving cyclone which only gradually turns to the right (slow recurvers). As shown in Table 2.1, the large majority of sharply recurving cyclones in this study recurved during the months of September through November, while most of the slowly recurving cyclones did so during June through September. Since sharp recurvature occurs primarily during the autumn months when the westerlies associated with the mid-latitudes begin migrating equatorward, sharp recurvature is likely caused by troughs penetrating into the tropical and sub-tropical atmosphere while slow recurvature, which occurs primarily during the summer months, is likely caused by a weakness in the sub-tropical ridge axis.

Table 2.1: Number of cyclones which occurred per month and percentage of total for each cyclone data set.

	Sharply Recurving Cyclones		Slowly Recurving Cyclones		Left Turning Cyclones		Non Recurving Cyclones	
JAN	1	2%	0	0%	0	0%	2	2%
FEB	0	0	0	0	0	0	0	0
MAR	1	2	0	0	0	0	0	0
APR	2	3	0	0	1	3	2	2
MAY	3	5	1	4	0	0	1	1
JUN	5	8	3	13	0	0	8	9
JUL	2	3	5	21	2	7	17	20
AUG	3	5	4	17	9	31	17	20
SEP	10	16	9	38	6	21	16	19
OCT	19	30	2	8	9	31	9	11
NOV	13	21	1	4	1	3	8	9
DEC	4	6	0	0	1	3	5	6
TOTALS	63	100 %	24	100 %	29	100 %	85	100 %

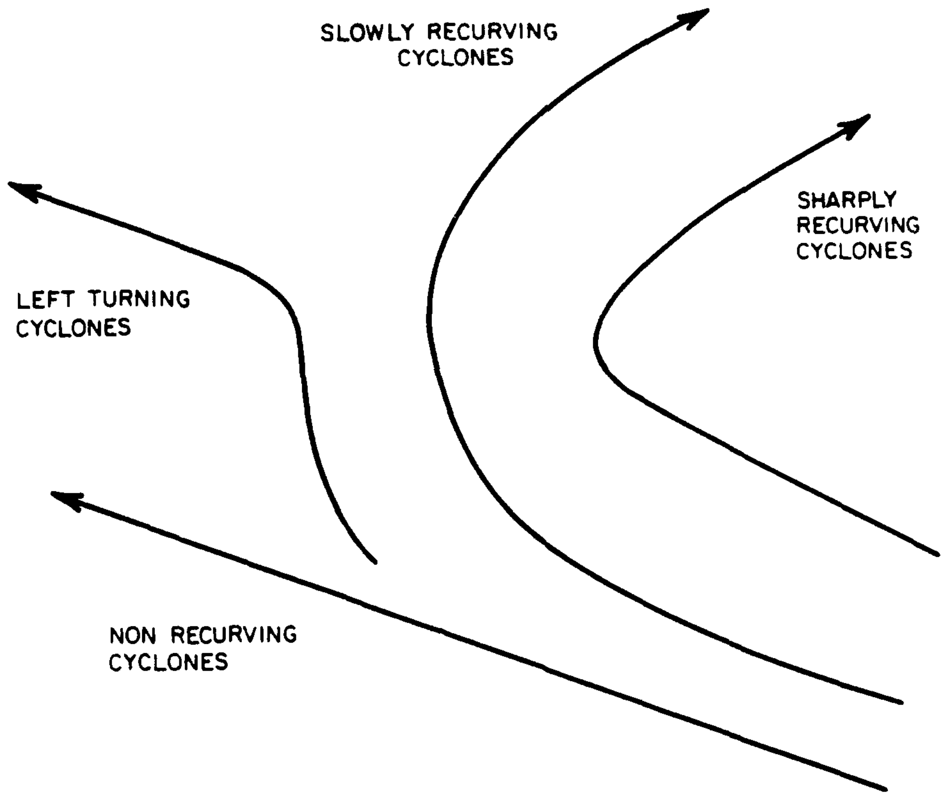


Figure 2.3: Typical tracks of the four basic types of cyclones analyzed in this study.

Before discussing the four types of cyclone tracks in detail, a formal definition of tropical cyclone recurvature is given. According to the Joint Typhoon Warning Center (JTWC 1988), tropical cyclone recurvature is "The turning of a tropical cyclone from an initial path west and poleward to east and poleward". As shown in Fig. 2.4, JTWC emphasizes the location at which the cyclone's track first takes on an eastward component of motion. In this study, the location where the sharply recurving and slowly recurving cyclones first deviate to the right from their previous west-northwest track is of primary importance. This deviation in the cyclone track marks the location where the surrounding environment first begins to change the direction of the sharply recurving and slowly recurving cyclones. This point of initial recurvature will be defined as the "beginning of Recurvature", or R point. Figure 2.5 shows an example of a slowly and sharply recurving cyclone and the associated R point.

A sharply recurving cyclone in this study is defined as a cyclone which changes direction a minimum of 45° to the right of its' previous west-northwest course within thirty-six

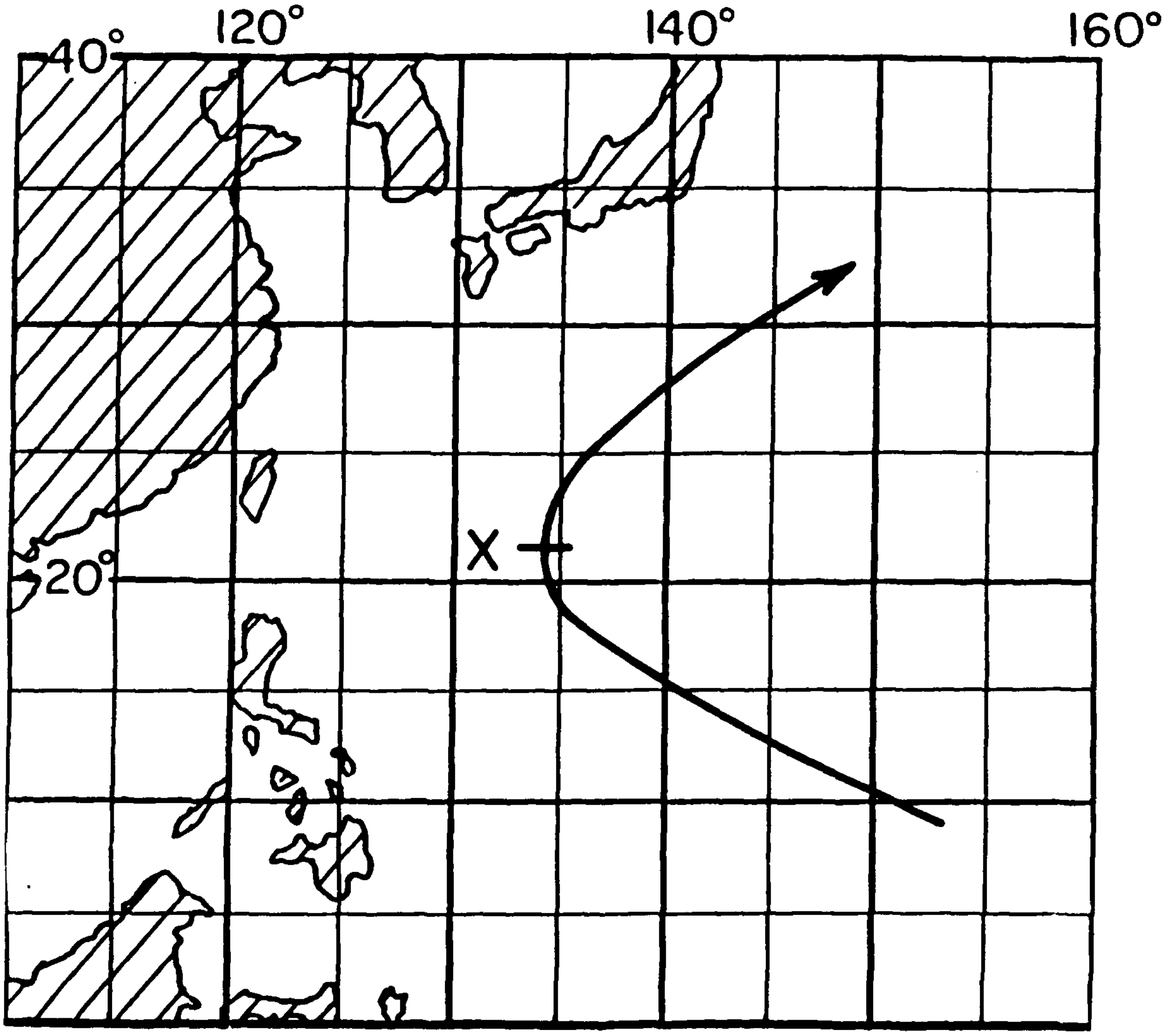


Figure 2.4: A typical recurving cyclone track. According to JTWC (1988), a cyclone undergoes recurvature when the cyclone first takes on an eastward component of motion (shown here by the letter "X").

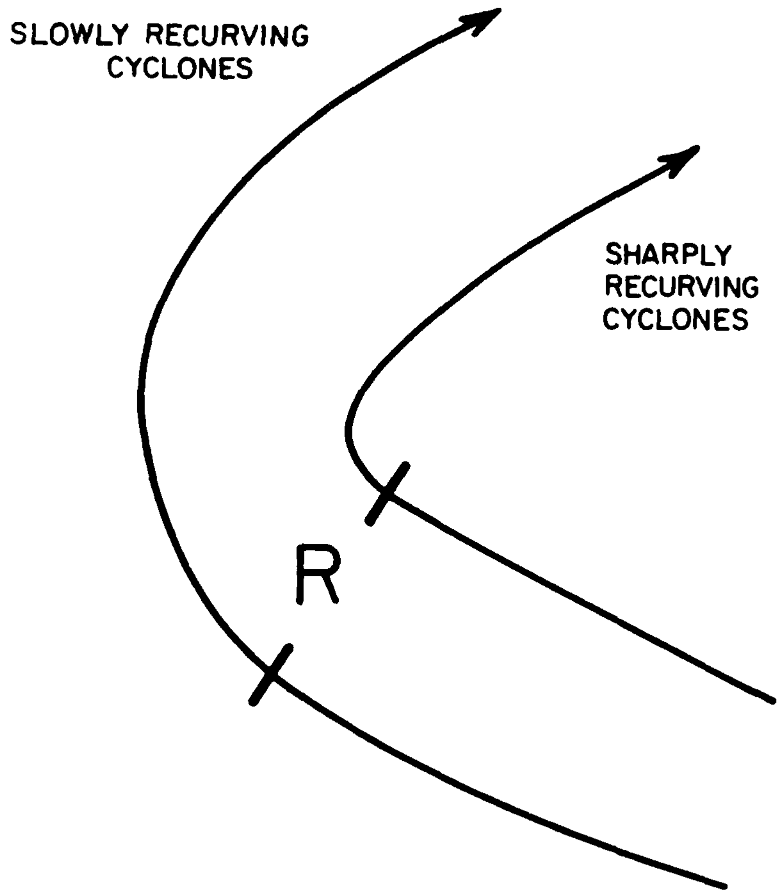
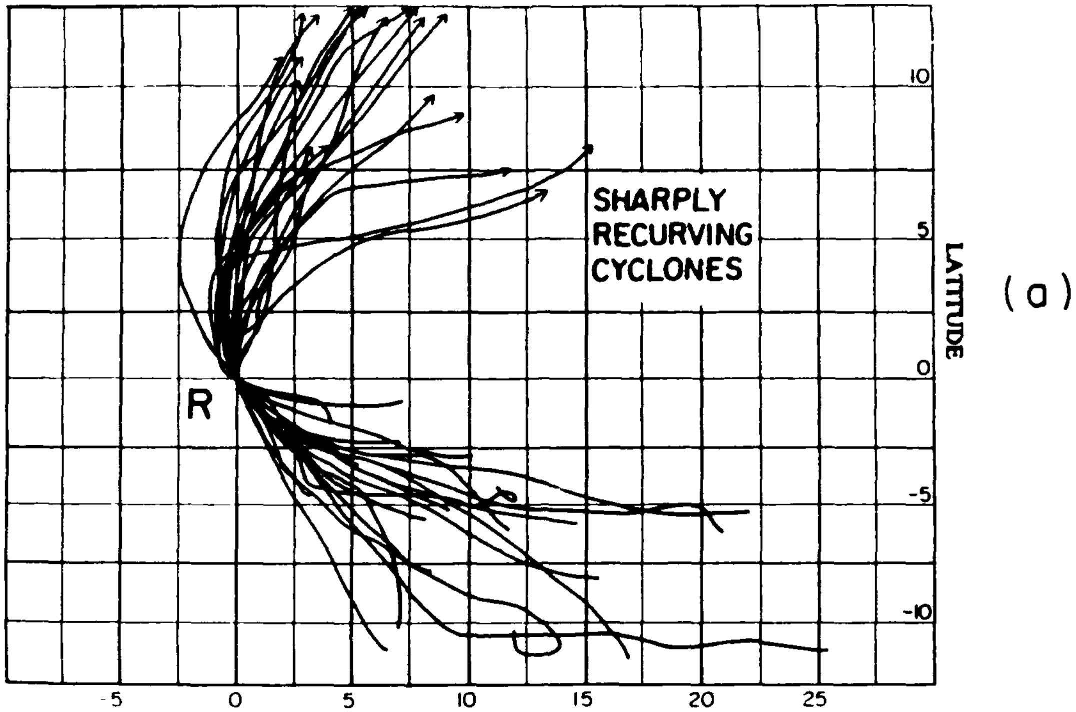


Figure 2.5: Typical tracks of a sharply recurving and slowly recurving cyclone. The large "R" represents the location where the sharply recurving and slowly recurving cyclones first begin to turn to the right from their west-northwest track.

hours after passing the R point. The cyclone must also have undergone recurvature (by JTWC definition) within 48 hours after passing the R point. In addition, sharply recurving cyclones must move on a course between 260° and 330° for a minimum of 24 hours prior to reaching the R point. This last restriction is necessary so that any changes which occur in the wind fields prior to the beginning of recurvature can be observed. A majority of the cyclones which recurved sharply had west-northwest tracks which lasted for more than 48 hours. Figure 2.6 shows the tracks of the 63 sharply recurving cyclones which were analyzed.

Slowly recurving cyclones were those cyclones which changed direction a minimum of 30° to the right of their previous west-northwest course within thirty-six hours after passing the R point. These slowly recurving cyclones must also have undergone recurvature within 72 hours after passing the R point. In addition, these cyclones must have been moving on a course between 260° and 330° for a minimum of 12 hours prior to reaching the R point. This last restriction limited the number of slowly recurving cyclones which could be analyzed for this study to 24 (Fig. 2.7), because most cyclones which gradually recurve in the northwest Pacific were moving on a course greater than 330° from their inception (ie., named storm status), and thus do not fall under the definition of a "slowly recurving cyclone" as adopted for this study.

A left turning cyclone is defined as a cyclone which is on a northerly course but instead of recurving off to the northeast, it turns back to the left and resumes a west-northwest course. In this study, the location where left turning cyclones begin to resume a west-northwest track is termed the "L point". The L-point is similar to the R-point of sharply and slowly recurving cyclones, but instead of the cyclone turning to the right, it turns to the left. A more precise definition of a left turning cyclone is a cyclone which was moving on a course between 320° and 045° for a minimum of 36 hours prior to reaching the L point. After passing the L point, the cyclone must take on a heading between 320° and 250° for a minimum of 36 hours. Figure 2.8 shows the tracks of the 29 left turning cyclones which were identified and analyzed.



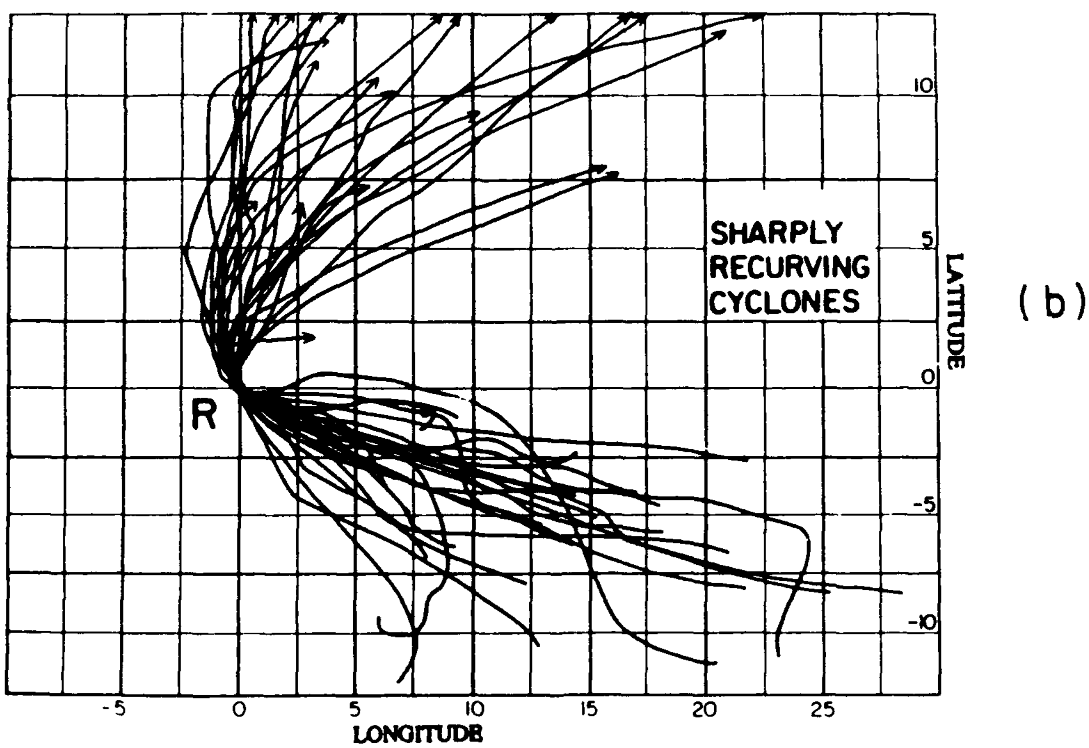


Figure 2.6: a-c. The tracks of the 63 sharply recurving cyclones which were analyzed in this study. Each sharply recurving cyclone track is drawn with respect to the R point. Approximately 21 recurving cyclones are shown in each panel.

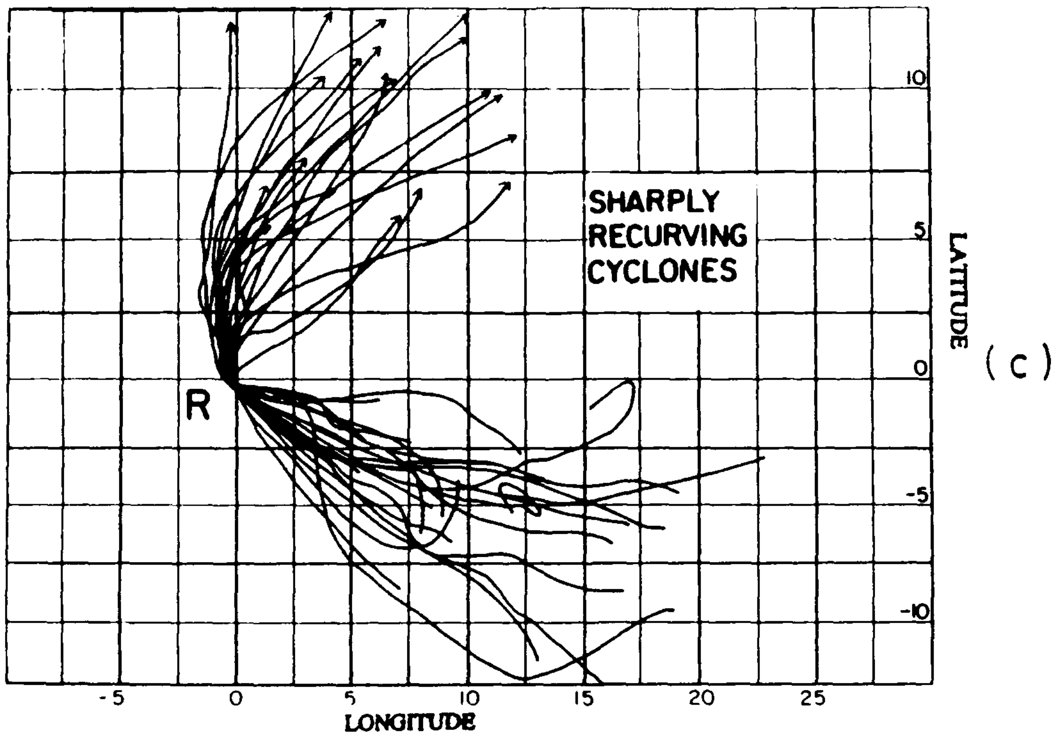


Figure 2.6: c. Continued.

To differentiate sharply recurving and slowly recurving cyclones from those cyclones which continue moving west throughout their lifetimes, a non-recurving cyclone data set was assembled and analyzed. The non-recurving cyclones were defined as cyclones which tracked between 260° and 320° throughout their lifetime[2]. Figure 2.9 shows the tracks of the 85 non-recurving cyclones which were analyzed in this study.

In addition to the four cyclone classifications discussed above, three additional cyclone data stratifications were made according to direction of motion, ie., West, North, and Northeast. Westward moving cyclones included any cyclone which moved between 240 and 315°, northward moving cyclones moved between 315 and 045°, and northeastward moving cyclones moved between 020 and 090°. These three additional data sets were analyzed so that quantitative comparisons could be made between the recurving cyclone

[2]If the cyclone should deviate from its' west-northwest course (260-320 degrees), and this deviation does not last longer than 24 hours, then the cyclone is still considered a non-recurving cyclone.

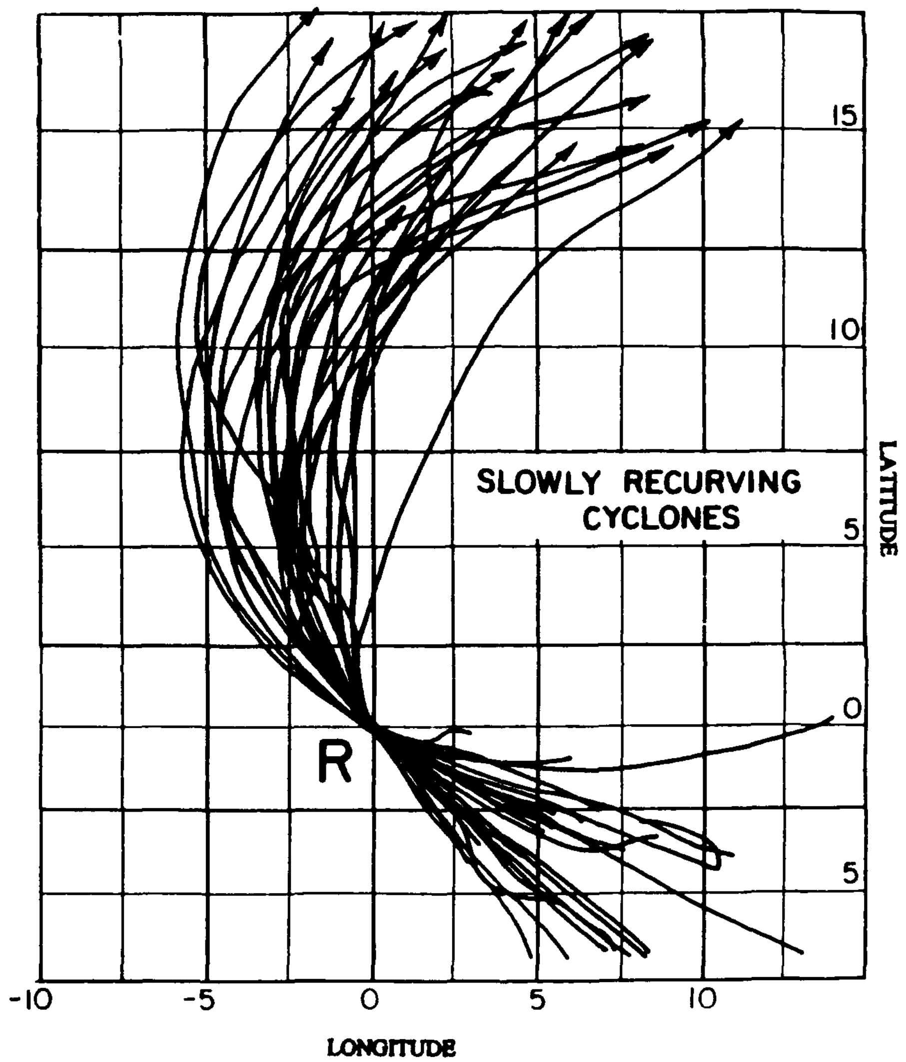


Figure 2.7: The tracks of the 24 slowly recurving cyclones which were analyzed in this study. Each slowly recurving cyclone track is drawn with respect to the R point.

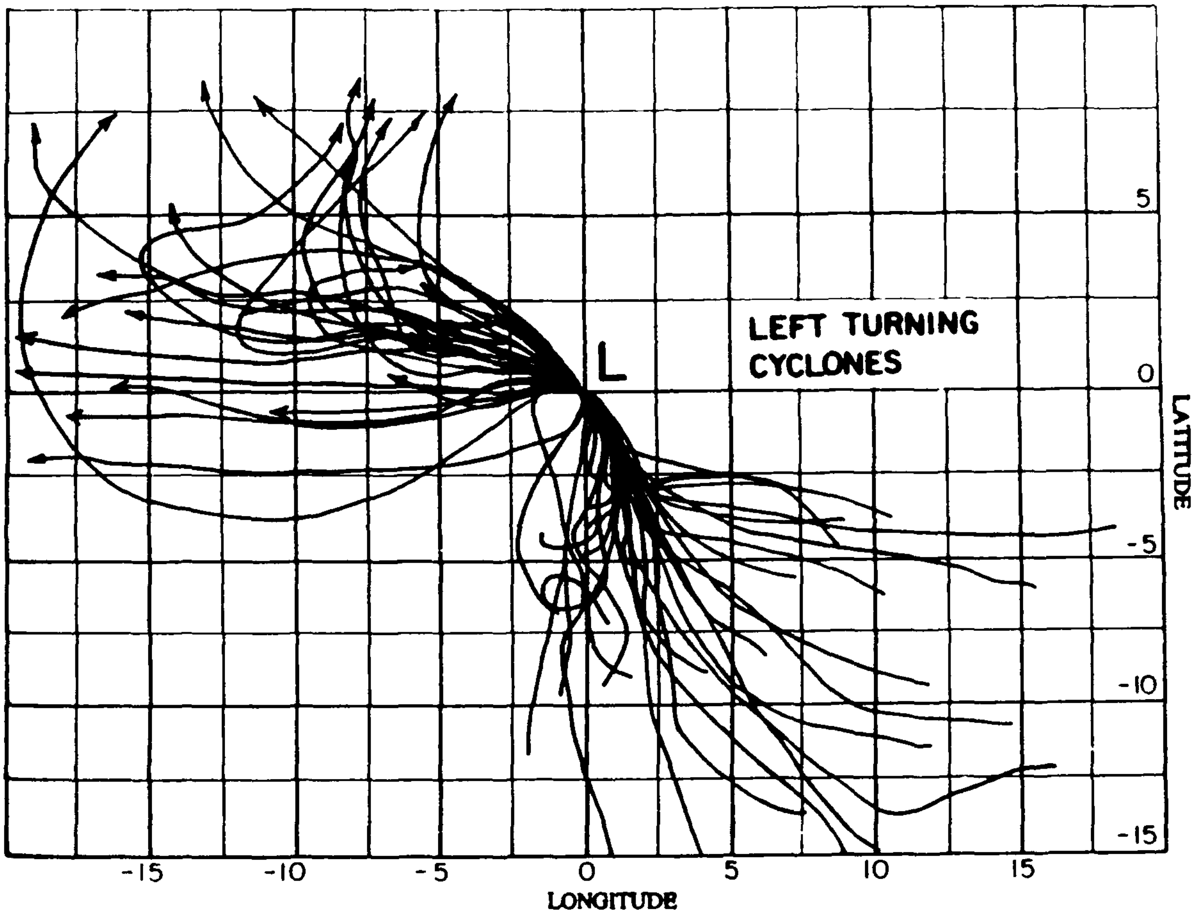


Figure 2.8: The tracks of the 29 left turning cyclones which were analyzed in this study. Each left turning cyclone track is drawn with respect to the L point.

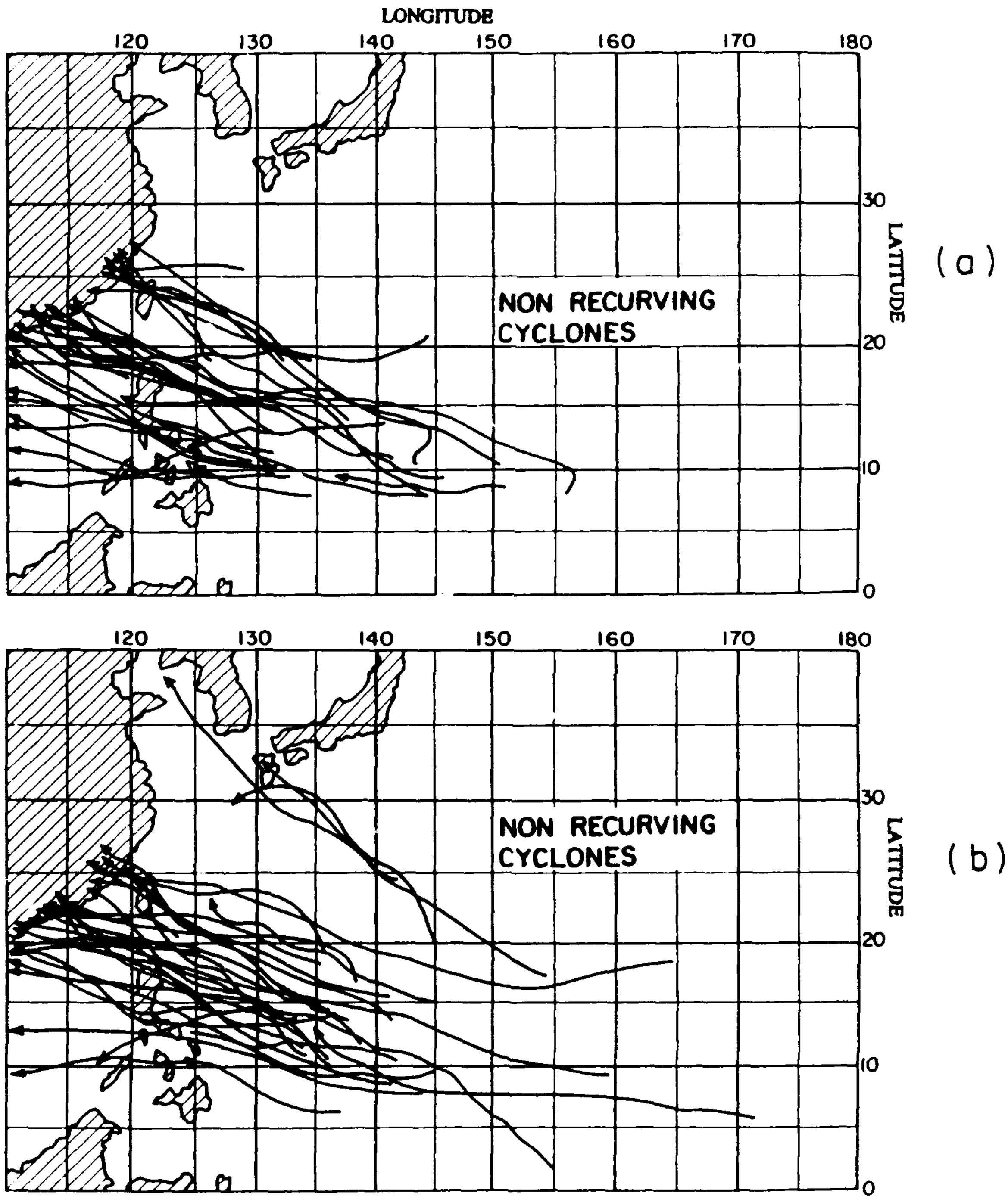


Figure 2.9: a-c. The tracks of the 85 non-recurving cyclones which were analyzed. Approximately 28 non-recurving cyclones are shown in each panel.

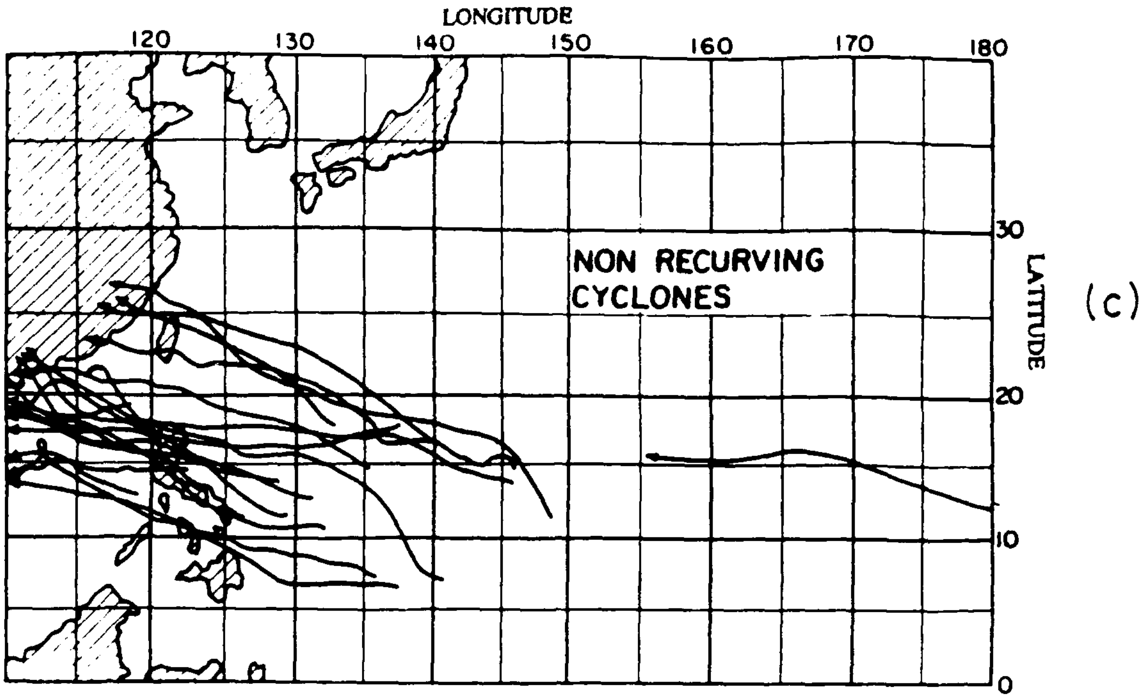


Figure 2.9: c. Continued.

data sets. Table 2.2 summarizes the directional classes for westward, northward and northeastward moving cyclones.

Table 2.2: Description of the cyclones stratified by direction.

Stratification	Description
West moving cyclones	240° < cyclone direction < 315°
North moving cyclones	315° < cyclone direction < 045°
Northeast moving cyclones	020° < cyclone direction < 090°

2.3 Cyclone Time Periods

To observe temporal changes of the environmental wind fields surrounding these cyclones, tracks of the sharply recurving, slowly recurving and left turning cyclones are divided into 24 hour time segments. Time was measured with respect to the R–point for the sharply recurving and slowly recurving cyclones and to the L–point for the left turning cyclones. By orienting and analyzing the cyclone data in this fashion, it was possible to examine how synoptic scale wind fields interacted with the cyclone circulations prior to and after, the cyclones began recurving or resumed a west-northwest course in the case of the left turning cyclones.

The sharply recurving cyclone tracks were divided into five consecutive 24 hour time periods (Fig. 2.10); the first three time periods, R0, R1 and R2, occur as the cyclones were moving on a west–northwest course before the tropical cyclone reached the R–point, while the fourth and fifth time periods (ie., R3 and R4) occurred after the cyclone has passed the R point. Similarly, slowly recurving cyclone tracks were divided into six consecutive 24 hour time periods (Fig. 2.10); the first two time periods, SR1 and SR2, occur as the cyclones move west–northwest before the R point. The remaining four periods, SR3, SR4, SR5, and SR6, occurred after the cyclone passed the R point. As shown in Fig. 2.10, sharply recurving and slowly recurving cyclones during period 1 (R1, SR1), period 2 (R2, SR2) and period 3 (R3, SR3) are concurrent to one another relative to the R point. By stratifying the cyclones in this fashion comparisons can be made between slowly and sharply recurving cyclones as they approach and pass the R point. Left turning cyclone tracks were divided into four consecutive 24 hour time periods (Fig. 2.10). The first two time periods, L3 and L4, occur before the cyclone reached the L point while the remaining two time periods, L5 and L6, occurred after the cyclone passed the L point.

The non-recurving cyclone tracks were divided up differently from the previous three cyclone data sets. Since no track reference point (equivalent to L or R) for the non-recurving cyclones was designated the entire length of each non-recurving cyclone track was divided into three equal periods: the first period, NR1, represents the first 1/3 of the cyclone track and so forth for periods NR2 and NR3. Although non-recurving cyclone tracks varied temporally and spatially, the average length of each NR period was 50 hours. Figure 2.10 shows a typical non-recurving track divided into three time periods. Figure 2.11 and Table 2.3 summarize mean speed and direction information for sharply recurving, slowly recurving, left turning and non-recurving cyclone time periods.

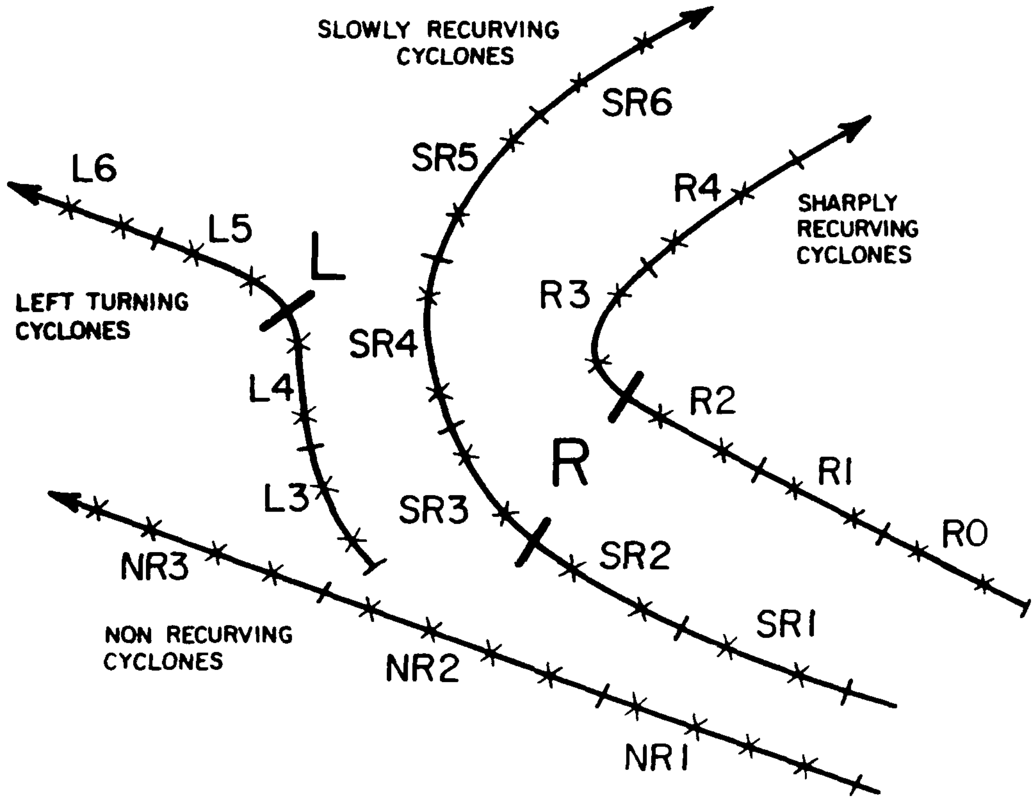


Figure 2.10: The sharply recurving (R0–R4), slowly recurving (SR1–SR6), left turning (L3–L6) and non-recurving (NR1–NR3) cyclone tracks divided into individual time periods. Table 2.3 and Fig. 2.11 summarize individual characteristics of each time period. The small X characters on the cyclone tracks represent the time (00 and 12 UTC) when rawinsonde data was collected from the surrounding northwest Pacific rawinsonde network.

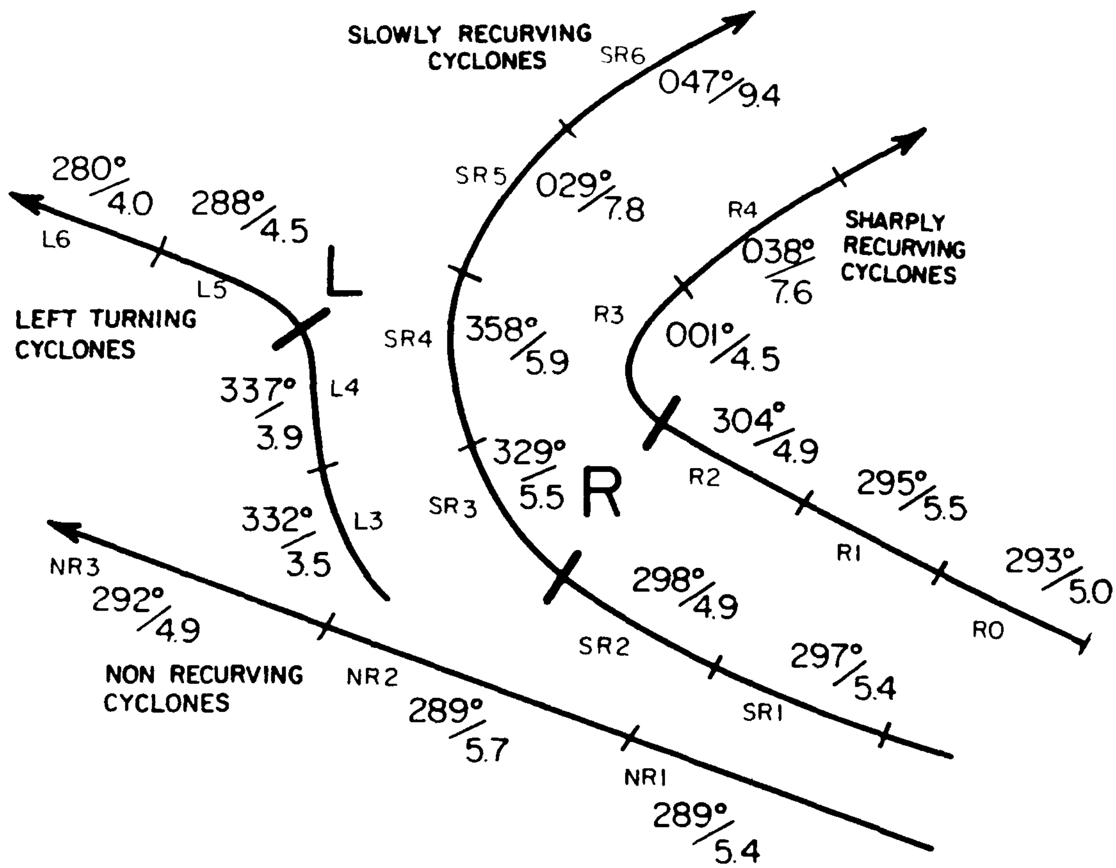


Figure 2.11: Composite average speed and direction of each of the sharply recurving, slowly recurving, left turning and non-recurving cyclone time periods. Units in ms^{-1}.

Table 2.3: Summary of the sharply recurving, slowly recurving, left turning and non-recurving time periods.

Name	Time Period	Description	Average Composite Direction (°)	Speed (ms^{-1})
	RO	48-72 h before beginning recurvature	293 (WNW)	5.0
Sharply	R1	24-48 h before beginning recurvature	295 (WNW)	5.5
Recurving	R2	0-24 h before beginning recurvature	304 (WNW)	4.9
Cyclones	R3	0-24 h after beginning recurvature	001 (N)	4.5
	R4	48-72 h after beginning recurvature	038 (NE)	7.6
	SR1	24-48 h before beginning recurvature	297 (WNW)	5.4
Slowly	SR2	0-24 h before beginning recurvature	298 (WNW)	4.9
Recurving	SR3	0-24 h after beginning recurvature	329 (NNW)	5.5
Cyclones	SR4	24-48 h after beginning recurvature	358 (N)	5.9
	SR5	48-72 h after beginning recurvature	029 (NE)	7.8
	SR6	72-96 h after beginning recurvature	047 (NE)	9.4
Left	L3	24-48 h before turning left	332 (NNW)	3.5
Turning	L4	0-24 h before turning left	337 (NNW)	3.9
Cyclones	L5	0-24 h after turning left	288 (WNW)	4.5
	L6	24-48 h after turning left	280 (WNW)	4.0
Non	NR1	First 1/3 of track	289 (WNW)	5.4
Recurving	NR2	Second 1/3 of track	289 (WNW)	5.7
Cyclones	NR3	Third 1/3 of track	292 (WNW)	4.9

As was discussed at the beginning of this chapter, a rawinsonde compositing technique was employed to analyze the environmental wind fields of recurving, left turning and non-recurving cyclones. Table 2.4 presents a summary of the average number of rawinsonde observations throughout the troposphere in octants 1, 2 and 3 at various radii for the sharply recurving, slowly recurving, left turning and non-recurving cyclone for each of the specified time periods. In general, the smallest number of observations are located close to the cyclone within 4°, while the numbers increase at larger radii. In addition, the initial time periods of the sharply recurving cyclones (period R0), slowly recurving cyclones (period SR1) and left turning cyclones (period L3) had fewer observations then the remaining sharply recurving, slowly recurving and left turning cyclone time periods, respectively. This difference is primarily due to the initial locations of these cyclones during these time periods, tending to be farther south and east where there are fewer rawinsonde observation stations. As the cyclones move west and north, they encounter a higher density rawinsonde observational network.

Excluding the non-recurving cyclones, the average number of observations in each octant is 7 at 4°, 16 at 6°, and 21 at 8°. In the remaining three radii, the average number of observations is in excess of 20. Although data is limited at 4°, it is believed an adequate number of observations occur close to the cyclone's center, especially for the sharply recurving cyclones, to allow for examination of how the synoptic scale wind fields interact with the cyclone's circulation.

2.4 Summary

Previous research on recurvature showed the environmental winds poleward and westward of the cyclone were critical for identifying recurvature/non-recurvature. What has not been shown previously is how the synoptic environment interacts with the cyclone's circulation prior to recurvature. The advantage of this study over previous recurvature studies is that sufficient data were available to permit analysis of how environmental wind fields throughout the troposphere change as the recurving cyclones move westward towards the point of beginning recurvature. Another unique feature of this study is that

Table 2.4: Number of rawinsonde observations in octants 1 (north), 2 (northwest) and 3 (west) for (A) sharply recurving, (B) slowly recurving, (C) non-recurving and (D) left turning cyclone time periods.

A

Sharply Recurving Cyclone Time Periods

Radius From TC Center	RO Octant			R1 Octant			R2 Octant			R3 Octant			R4 Octant		
Radius	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
4°	6	6	6	8	6	5	9	12	11	17	15	12	16	22	16
6°	9	11	5	13	15	16	22	18	24	26	38	17	33	32	32
8°	14	14	17	22	28	22	29	35	23	43	48	47	45	62	54
10°	22	26	17	32	40	20	45	53	32	58	90	37	50	73	56
12°	32	39	23	47	51	27	61	81	36	76	102	52	58	72	78
14°	35	44	20	65	58	31	67	107	33	62	79	71	57	54	80

B

Slowly Recurving Cyclone Time Periods

	SR1 Octant			SR2 Octant			SR3 Octant		
Radius	1	2	3	1	2	3	1	2	3
4°	1	2	0	2	3	2	4	5	3
6°	3	2	0	10	4	9	22	12	8
8°	5	5	0	13	12	8	24	18	14
10°	11	7	6	18	22	8	24	27	19
12°	14	17	13	29	29	15	30	28	15
14°	27	26	9	32	27	21	31	30	16

	SR4 Octant			SR5 Octant			SR6 Octant		
Radius	1	2	3	1	2	3	1	2	3
4°	15	4	9	6	8	7	4	5	13
6°	17	11	16	9	15	4	7	10	9
8°	17	13	23	12	9	14	8	13	7
10°	23	25	28	14	14	21	3	7	13
12°	22	21	31	12	16	29	3	7	5
14°	21	26	21	8	15	9	1	13	19

Table 2.4: Continued

C

Non-Recurving Cyclone Time Periods

	NR1			NR2			NR3		
	Octant			Octant			Octant		
Radius	1	2	3	1	2	3	1	2	3
4°	21	30	27	76	63	32	48	53	48
6°	53	54	34	150	134	59	64	35	63
8°	89	73	56	197	169	83	56	27	47
10°	130	135	57	211	206	105	74	20	42
12°	197	182	82	248	192	108	70	26	25
14°	232	262	77	244	157	108	76	20	25

D

Left Turning Cyclone Time Periods

	L3			L4			L5			L6		
	Octant			Octant			Octant			Octant		
Radius	1	2	3	1	2	3	1	2	3	1	2	3
4°	4	8	2	2	3	7	13	8	9	8	7	6
6°	4	6	6	10	19	12	18	19	11	19	17	17
8°	6	18	7	18	25	11	22	29	16	20	23	23
10°	23	23	10	29	37	16	22	38	20	15	29	22
12°	36	41	12	30	42	29	21	26	22	21	37	27
14°	34	54	22	19	37	24	25	35	37	19	30	28

cyclones that moved north and then turned left are also analyzed along with non-recurving cyclones.

Chapter 3

ENVIRONMENTAL WIND FIELDS ASSOCIATED WITH SHARPLY RECURVING, SLOWLY RECURVING, LEFT TURNING AND NON-RECURVING CYCLONES

3.1 Introduction

As discussed in Chapter 1, the main objective of this study was to identify features in the wind fields surrounding tropical cyclones which are conducive to recurvature. This objective is attained by first finding locations, measured relative to the center of the cyclone, which best differentiate recurving from non-recurving cyclones. This is done by examining how the environmental wind fields of non-recurving cyclones differ from those of sharply recurving and slowly recurving cyclones prior to the beginning of recurvature.

Table 3.1 shows zonal and meridional wind differences between sharply recurving cyclones prior to beginning recurvature versus those of non-recurving cyclones. At 8° from the center of the cyclone the largest differences in the wind fields occur in the zonal components in the mid and upper troposphere to the north, northwest and west (octants 1, 2 and 3). This result is not surprising in that the northwest region (octants 1, 2 and 3) is where westerly winds associated with an eastward moving trough in the mid-latitude westerly wind regime will first begin to interact with the cyclone's outer circulation.

Zonal and meridional wind differences between slowly recurving cyclones prior to beginning recurvature (period SR2) and non-recurving cyclones are shown in Table 3.2. As can be seen, the differences are significantly less then for the sharply recurving cyclones, but the largest differences still occur for the zonal component in the northwest region (octant 2). Again this is not a surprising result in that the large scale synoptic pattern favorable for slow recurvature is a weakening of the sub-tropical ridge. A west-

Table 3.1: Zonal (top) and meridional (bottom) wind differences between sharply recurving cyclones prior to recurvature (period R2) and the non-recurving cyclones. Units in ms^{-1}.

Sharply Recurving Cyclones (Period R2) Minus Non-recurving Cyclones

Zonal Wind Differences–8 Degrees from Cyclone's Center

P (mb)	Oct 1	Oct 2	Oct 3	Oct 4	Oct 5	Oct 6	Oct 7	Oct 8
100	14.5	16.6	7.8	1.8	4.3	3.5	2.9	9.3
200	15.4	16.3	8.7	3.7	3.0	0.4	1.9	4.8
300	9.7	17.6	10.0	2.4	1.4	1.3	0.6	3.7
400	8.5	13.8	8.6	-0.4	-0.1	4.2	-0.7	3.7
500	6.6	11.6	5.9	-0.1	-1.2	-0.5	-0.2	3.7
600	3.8	6.8	2.4	-1.3	-2.5	-0.5	1.4	4.0
700	3.0	[illegible]3	-0.7	-1.8	-2.1	1.7	0.7	2.8
800	3.1	2.2	-0.7	-2.1	-3.3	2.5	-0.5	2.7
Layer Ave	8.1	11.2	5.3	0.3	-0.1	1.6	0.8	4.3

Meridional Wind Differences–8 Degrees from Cyclone's Center

P (mb)	Oct 1	Oct 2	Oct 3	Oct 4	Oct 5	Oct 6	Oct 7	Oct 8
100	6.4	4.9	2.0	1.4	1.7	0.2	0.8	4.2
200	10.9	1.3	-1.9	-0.8	1.9	-0.3	-0.6	4.3
300	5.1	1.4	-3.8	-1.1	0.7	-0.5	1.1	4.2
400	3.8	0.9	-0.3	0.9	-0.1	-1.9	2.9	2.3
500	2.6	0.4	1.3	0.2	-1.2	-0.6	1.7	0.5
600	3.1	0.9	-0.6	-1.0	-2.6	-2.3	1.2	0.3
700	1.3	1.9	-0.3	-2.0	-1.7	-0.1	0.7	-0.3
800	1.6	0.7	-0.1	-1.1	0.2	0.2	1.3	0.1
Layer Ave.	4.4	1.6	-0.5	-0.4	-0.1	-0.7	1.1	2.0

northwest moving cyclone southwest of the ridge axis will first encounter this weakness on the northwest side of the cyclone (Fig. 3.1).

Table 3.2: Zonal (top) and meridional (bottom) wind differences between slowly recurving cyclones prior to recurvature (period SR2) and the non-recurving cyclones. Units in ms^{-1}.

Slowly Recurving Cyclones (Period SR2) Minus Non-recurving Cyclones

Zonal Wind Differences–8 Degrees from Cyclone's Center

P (mb)	Oct 1	Oct 2	Oct 3	Oct 4	Oct 5	Oct 6	Oct 7	Oct 8
100	-3.0	8.5	-2.0	-2.7	4.0	4.4	0.8	2.2
200	-1.2	3.4	2.6	-0.7	1.9	0.2	1.6	3.8
300	-2.6	2.7	1.0	-1.9	1.3	1.2	-1.1	1.0
400	-1.0	3.7	-0.5	-0.2	-3.1	-1.3	-1.9	-3.6
500	0.5	4.5	1.2	2.1	-1.3	-1.8	1.8	-2.2
600	0.7	5.8	0.0	-0.3	0.9	-1.9	-0.1	-2.3
700	2.2	4.1	0.7	-1.1	-0.4	-1.3	-0.3	0.1
800	3.2	2.8	-2.1	1.7	0.1	0.0	0.5	-2.1
Layer Ave.	-0.2	4.5	0.1	0.4	0.4	-0.1	0.2	-0.4

Meridional Wind Differences–8 Degrees from Cyclone's Center

P (mb)	Oct 1	Oct 2	Oct 3	Oct 4	Oct 5	Oct 6	Oct 7	Oct 8
100	4.3	-0.5	-1.6	-0.9	1.9	-0.6	1.9	-1.8
200	-0.4	-0.1	-1.1	1.1	-4.8	2.6	3.0	-1.8
300	2.3	4.5	-1.0	-0.1	-2.0	2.6	3.1	-1.1
400	3.4	4.4	0.8	3.0	1.5	2.2	0.4	0.2
500	1.2	3.8	1.5	-0.2	2.3	0.3	1.3	-1.2
600	2.0	3.4	-0.6	-2.7	-0.4	1.0	0.8	-1.7
700	2.5	2.4	-0.4	-3.0	0.3	0.5	0.3	-1.6
800	2.9	1.5	-1.0	-3.6	0.4	0.8	0.4	1.0
Layer Ave.	2.3	2.4	-0.4	-0.8	-0.1	1.2	1.4	-0.6

It is important to note two characteristics of the wind field differences shown in Tables 3.1 and 3.2. The first characteristic is that both the zonal and meridional wind field differences equatorward of the cyclone are negligible, even though both the sharply and slowly recurving cyclones were about to begin recurving within the next ~12 hours. This lack of difference shows that the environmental flow equatorward of the cyclone does

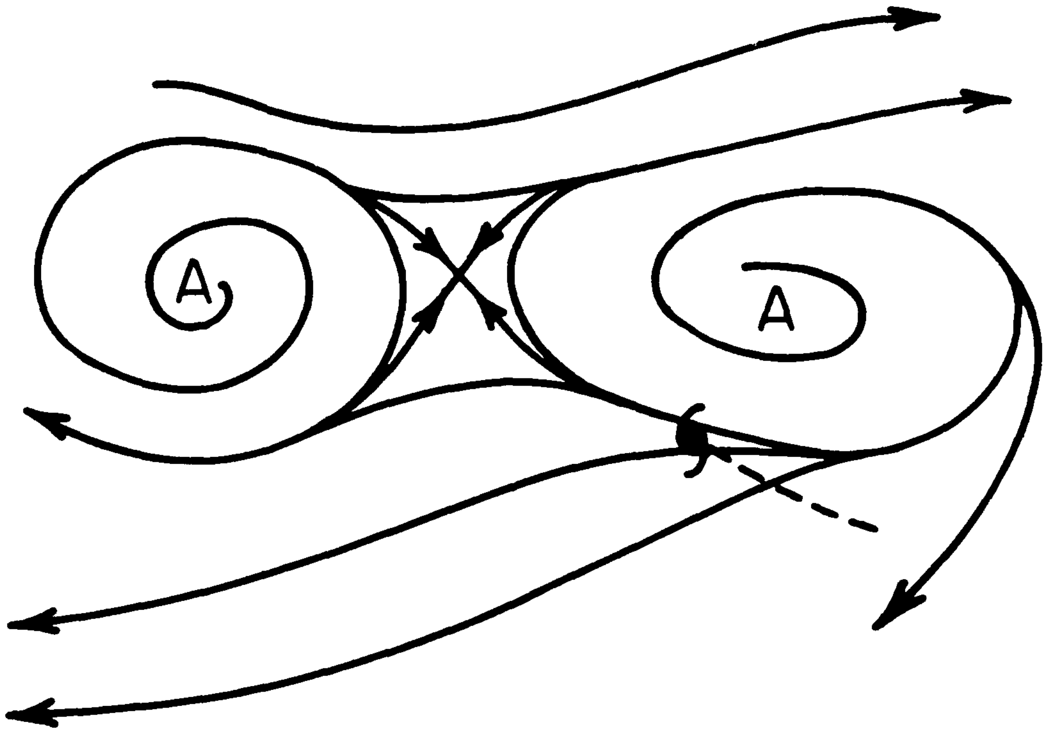


Figure 3.1: A west-northwest moving cyclone approaching the weakness in the sub-tropical ridge axis. Note the weakness in the ridge is located to the northwest of the cyclone.

not likely play a role in causing the cyclone to begin recurving. The second characteristic in these tables is that the zonal wind field differences in the northwest region were larger than the meridional wind differences, especially for the sharply recurving cyclones. Though not shown here, this characteristic was also found to occur in the northwest region at radial belts beyond 8°.

The largest wind field differences between cyclones which were moving west-northwest and about to begin recurving versus cyclones which moved west-northwest throughout their lifetimes occurred in the mid and upper troposphere in the northwest region (octants 1, 2 and 3). To find which locations show the most significant changes prior to recurvature, the zonal wind fields of the sharply recurving and slowly recurving cyclones were compared at periods 1, 2 and 3. [Note: slowly and sharply recurving cyclones begin to recurve between periods 2 and 3. During periods 1 and 2, the slow and sharply recurving cyclones were moving on a west-northwest course (see Fig. 2.11 for summary of cyclone directions)].

Table 3.3 shows the zonal wind and zonal wind differences for the sharply recurving cyclones at selected pressure levels in octant 2 (northwest) at radial belts 4 through 14°. At R1, the nearest significant positive zonal winds (>5 ms^{-1} throughout the layer) are located at 10° and beyond. At R2, significant positive zonal winds reach to within 6° of the cyclone. Although the zonal wind changes that occur between these two time periods are rather large, especially at 8 and 10°, the cyclones at R2 remain on a west-northwest course. Between periods R3 and R2, the zonal winds at 6° have changed significantly, shifting from a weak easterly component to a westerly component. It is between these two time periods that the cyclones begin sharp recurvature.

Table 3.4 shows the zonal wind and zonal wind differences for slowly recurving cyclones at selected pressure levels in octant 2 (northwest) extending from 4 to 14°. The nearest positive zonal winds at period SR1 are located at 12° beyond; at SR2, the positive zonal winds have penetrated close to 8°. Note the largest changes between these two time periods occurs at 8 and 10°, but again, the cyclones at SR2 remain on a west-northwest course. Between periods SR3 and SR2, the zonal winds at 6 and 8° shift from an easterly component to a westerly component. It is between these two time periods that the slowly recurving cyclones begin to recurve.

Tables 3.3 and 3.4 showed that both the sharply recurving and slow recurving cyclones had one feature in common; the cyclones did not begin to recurve until positive zonal winds penetrated to within 6° of the cyclone's center in octant 2. It was also shown that positive zonal winds could reach to within 8 and 10° of the centers of sharply recurving and slowly recurving cyclones and have no effect on changing their direction. It can be inferred from these results that the zonal winds at 6° to the northwest of the cyclone are likely to be crucial for determining if a cyclone is actually going to begin recurving or remain on a west-northwest course.

Although not explicitly shown in Tables 3.3 and 3.4, zonal winds at 8° are important for inferring if a cyclone might begin recurving in the near future or remain on a west-northwest course. As will be shown in subsequent sections of this chapter, tropical cyclones

Table 3.3: Zonal winds (top) and zonal wind differences (bottom) of the sharply recurving cyclones at periods R1, R2 and R3 in octant 2. Units in ms^{-1}.

Zonal Winds–Octant 2
Sharply Recurving Cyclones

	Radius from Cyclone's Center						
	4°	6°	8°	10°	12°	14°	
P (mb)							
200	-1.5	4.5	0.9	8.3	22.4	22.8	
350	-4.9	-2.7	-3.3	8.8	16.5	19.4	Period R1
500	-10.2	-2.8	-2.7	6.4	9.2	12.7	
200	-3.8	0.4	13.7	22.8	27.1	30.6	
350	-7.6	-0.2	11.9	18.4	23.9	25.1	Period R2
500	-12.4	-3.2	6.5	12.9	14.5	16.7	
200	1.7	16.0	20.5	29.5	33.5	35.5	
350	2.5	16.9	23.4	26.8	27.4	30.0	Period R3
500	-0.6	6.6	11.5	16.8	17.9	19.0	

Zonal Wind Differences–Octant 2

	Radius from Cyclone's Center						
	4°	6°	8°	10°	12°	14°	
P (mb)							
200	-2.3	-3.1	12.8	14.5	4.7	7.8	Period R2
350	-2.7	2.5	15.2	9.6	7.4	5.7	Minus
500	-2.2	-0.4	9.2	6.5	5.3	4.0	Period R1
200	5.5	15.6	6.8	6.7	6.4	4.9	Period R3
350	10.1	17.1	11.5	8.4	3.5	4.9	Minus
500	11.8	9.8	5.0	3.9	3.4	2.3	Period R2

Table 3.4: Zonal winds (top) and zonal wind differences (bottom) of the slowly recurving cyclones at periods SR1, SR2 and SR3 in octant 2. Units in ms^{-1}.

Zonal Winds–Octant 2
Slowly Recurving Cyclones

P (mb)	4°	6°	8°	10°	12°	14°	
	Radius from Cyclone's Center						
200	-3.2	-9.4	-4.9	-2.5	1.6	7.2	
350	-6.7	-7.4	-7.3	-2.6	3.1	5.1	Period SR1
500	-7.5	-7.1	-3.8	-0.6	5.0	5.7	
200	2.6	-3.6	-0.8	10.6	8.9	13.5	
350	-7.7	-5.4	-0.8	4.9	5.3	5.7	Period SR2
500	-11.4	-4.9	-0.6	4.3	3.6	2.9	
200	-0.9	1.8	6.3	12.2	11.0	16.1	
350	-4.8	0.6	4.0	4.3	7.4	9.9	Period SR3
500	-10.5	-1.5	3.7	3.2	5.1	7.2	

Zonal Wind Differences–Octant 2

P (mb)	4°	6°	8°	10°	12°	14°	
	Radius from Cyclone's Center						
200	5.8	5.8	4.1	13.1	7.3	6.3	Period SR2
350	-1.0	2.0	6.5	7.5	2.2	0.6	Minus
500	-3.9	2.2	3.2	4.9	-1.4	-2.8	Period SR1
200	-3.5	5.4	7.1	1.6	2.1	2.6	Period SR3
350	2.9	6.0	4.8	-0.6	2.1	4.2	Minus
500	0.9	3.4	4.3	-1.1	1.5	4.3	Period SR2

which have negative zonal winds at 8° from the center were not likely to begin recurving in the immediate future, whereas cyclones which did have positive zonal winds at this radius were possible candidates for recurvature.

SUMMARY

It was shown that the largest differences between the wind fields surrounding west-northwest moving cyclones prior to beginning recurvature and those of west-northwest moving cyclones which continue to move west-northwest throughout their lifetimes occurred in the northwest region of the cyclone. It was also shown that the wind fields at 6 and 8° from the center of the cyclone showed significant changes prior to, and immediately after, beginning recurvature. In addition, it was shown that the zonal wind field differences were larger than the meridional wind field differences. For these reasons, the rest of this study will examine in detail zonal wind fields for the sharply recurving, slowly recurving, non-recurving and left turning [3] cyclones at 6 and 8° north (octant 1), northwest (octant 2) and west (octant 3) of the cyclone. The wind fields at the other radii will be discussed in the appendix.

3.2 Zonal Wind Fields of the Sharply Recurving, Slowly Recurving, and Non-recurving Cyclones

3.2.1 Non-recurving Cyclones

Figures 3.2 and 3.3 show the 6° and 8° zonal wind profiles respectively for the three non-recurving time periods in octants 1, 2 and 3. As can be seen, the 6° zonal wind profiles show that zonal winds in all three octants for all three non-recurving time periods are from an easterly component throughout the troposphere except in octant 1 where the zonal winds in the upper troposphere are from a weak westerly component. The 8° zonal profiles (Fig. 3.3) show that the zonal winds in octant 1 at periods NR1 and NR2 are negative, but at period NR3, positive zonal winds have penetrated into the mid and

[3] Although not shown, the wind fields of the left turning cyclones also showed significant differences to the north and west of the cyclone.

upper troposphere. The zonal wind profiles in octant 2 also show that weak positive zonal winds have penetrated the 200-400 mb layer at period NR3. The zonal profiles in octant 3 show that the zonal winds for all three non-recurving time periods are from an easterly component throughout the troposphere.

SUMMARY

Tropical cyclones which moved west throughout their lifetimes were observed to be embedded in deep easterly flow at nearly all levels in the troposphere at 6°. The zonal wind fields at 8° were also from an easterly component throughout most of the troposphere except during the last time period, NR3. During the latter period, positive zonal winds have penetrated into the mid and upper troposphere to the north and northwest of the cyclone. These positive zonal winds are most likely associated with the mid latitude westerly wind regime and appeared during the last time period simply because non-recurving cyclones generally moved on a west-northwest course. Tropical cyclones which track in this direction will eventually move to higher latitudes and approach the southern limits of the mid latitude westerly wind regime. What is important to recognize is that westerlies penetrated the mid and upper troposphere 8° to the north and northwest of these cyclones and yet had no effect on changing the direction of motion.

3.2.2 Sharply Recurving Cyclones

Figure 3.4 shows the zonal wind profiles at 6° radius for the five sharply recurving time periods in octants 1, 2 and 3. Prior to the beginning of sharp recurvature, periods R0, R1 and R2, the 6° zonal wind profiles in octants 1 and 2 show the zonal winds are from an easterly component in the mid and lower troposphere, and from a weak westerly component in the upper troposphere. The zonal winds in octant 3 are from an easterly component at all levels of the troposphere. During these three time periods, the zonal profiles of the sharply recurving cyclones prior to the beginning of recurvature are similar to non-recurving cyclones profiles (Fig. 3.2) except for the positive zonal winds in the upper troposphere in octants 1 and 2. Since these relatively weak positive zonal winds occur during all three time periods prior to sharp recurvature, they are likely the result of

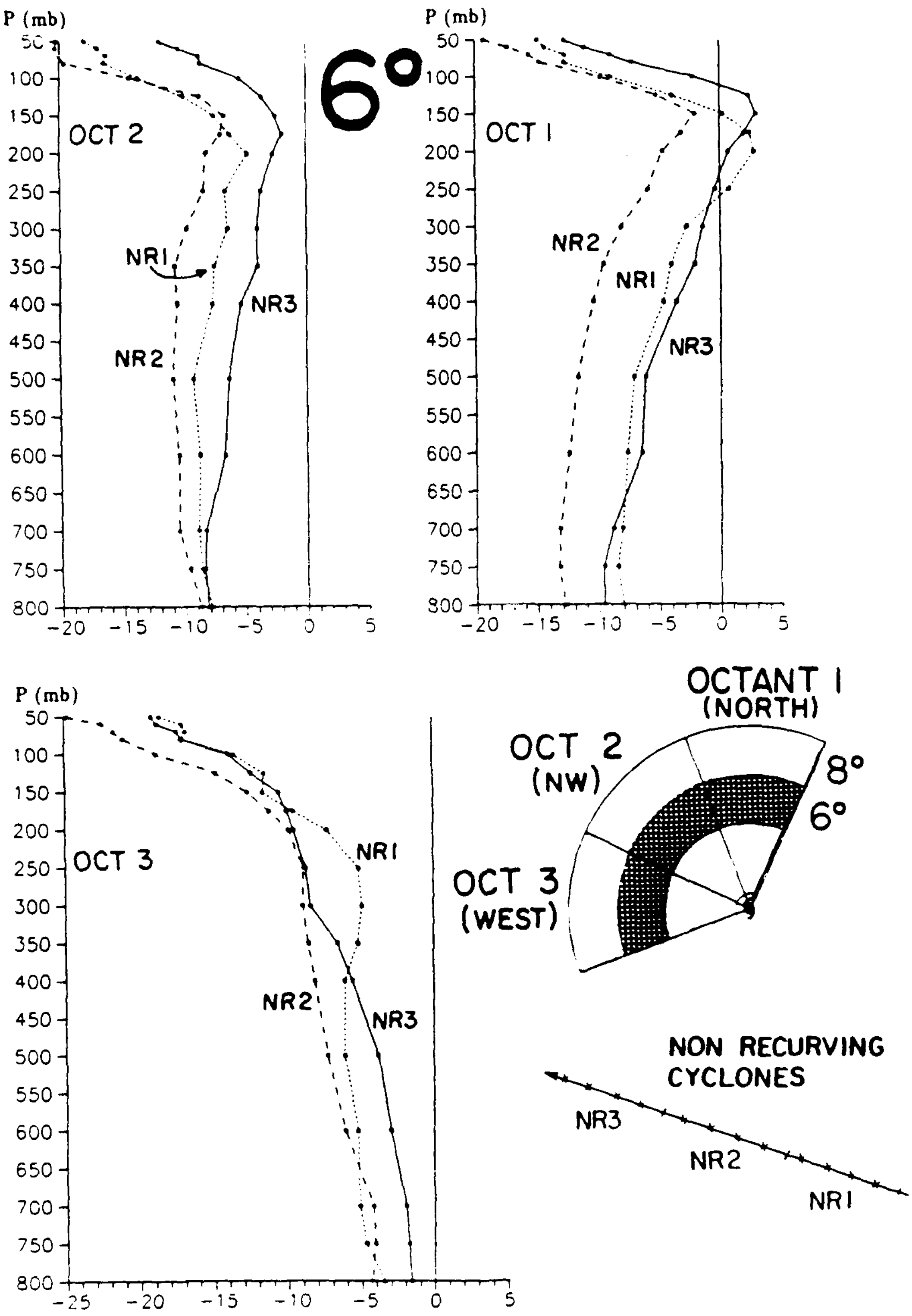


Figure 3.2: The 6° zonal wind profiles for the 3 non-recurving time periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units in ms^{-1}.

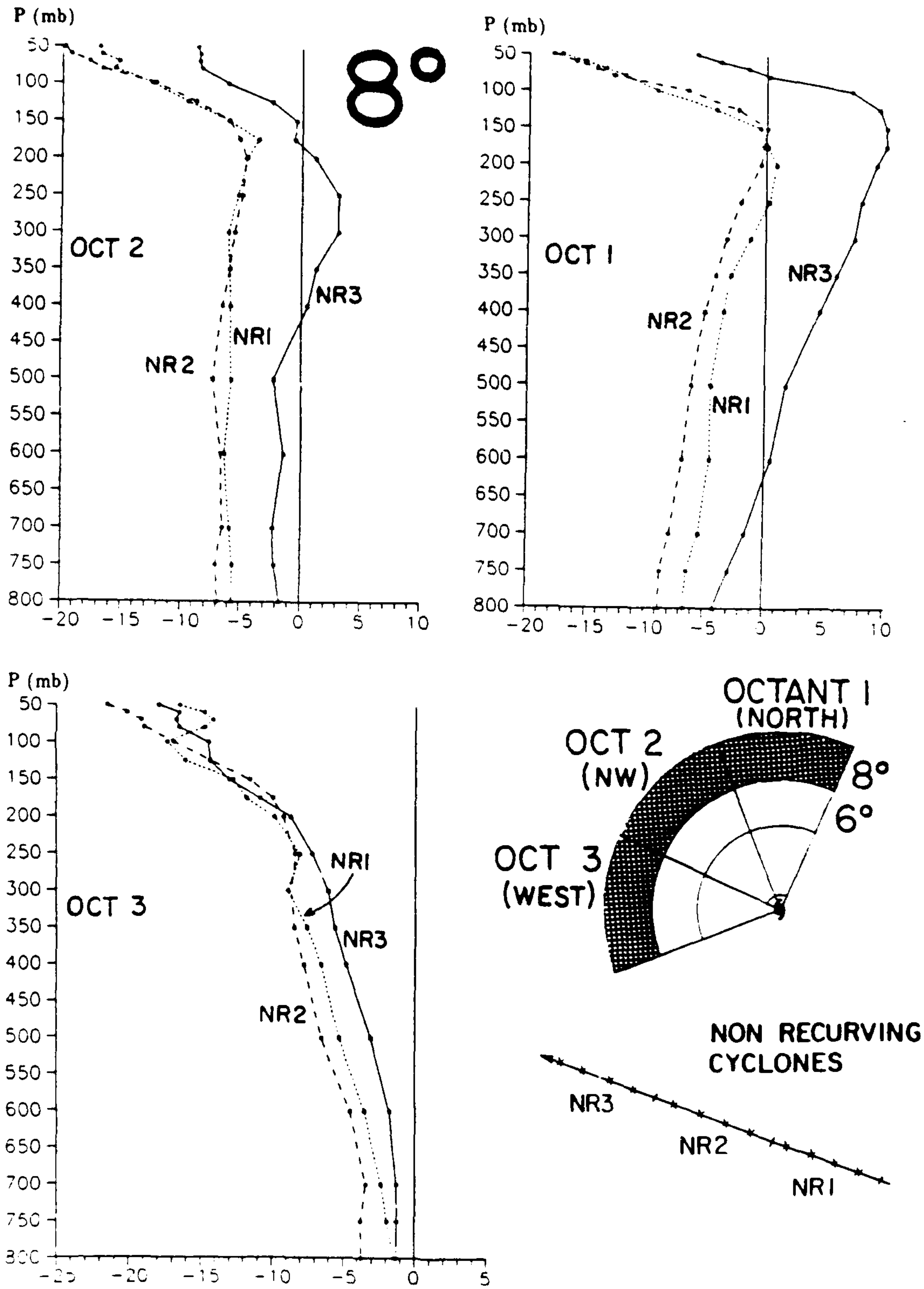


Figure 3.3: The 8° zonal wind profiles for the 3 non-recurving time periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units in ms^{-1}.

seasonal climatology and are not believed to be directly related to sharp recurvature (the cause of these winds will be discussed in more detail below).

Significant changes in the zonal wind fields have taken place in all three octants at period R3. During the previous three time periods, when the cyclones were moving west-northwest, zonal winds in the mid and upper troposphere in all three octants were from an easterly or weak westerly component. As the cyclones begin to recurve sharply during period R3, zonal winds in the mid and upper troposphere in all three octants shift to strong westerly components. Zonal wind differences for the first three time periods versus those of period R3 are very large, as summarized in Table 3.5. As the cyclones continued to recurve sharply off to the northeast (period R4) zonal profiles in all three octants become increasingly sheared from the west.

Table 3.5: Zonal wind differences for sharply recurving time periods R3 versus R2 (24 h change), and R2 and R0 (48 h change). The differences are taken at 6 degrees from the center of the cyclone in octants 1, 2 and 3. Units in ms^{-1}.

	Sharply Recurving Cyclones Zonal Wind Differences—6 Degrees					
	Octant 3 (West)		Octant 2 (Northwest)		Octant 1 (North)	
P (mb)	R3-R2	R2-R0	R3-R2	R2-R0	R3-R2	R2-R0
100	11.8	3.2	17.1	2.6	10.5	0.9
150	9.9	3.3	12.6	-1.1	7.4	-0.2
200	8.7	1.1	15.6	-0.5	7.4	0.2
250	8.7	1.7	19.4	-2.3	4.9	2.5
300	8.4	4.5	20.8	1.0	6.8	1.6
350	11.0	1.7	17.1	3.5	6.9	2.9
400	8.3	4.7	16.8	1.1	7.0	2.7
500	6.2	4.5	9.8	2.0	3.3	4.4
600	5.1	3.1	7.1	1.9	0.6	3.5
700	5.0	1.8	4.1	1.9	0.0	3.1
800	-0.4	-0.5	5.2	0.6	0.3	2.8

Zonal profiles at 8° for the five sharply recurving time periods are shown in Fig. 3.5. The zonal profiles in octants 1 and 2 for the first two sharply recurving time periods

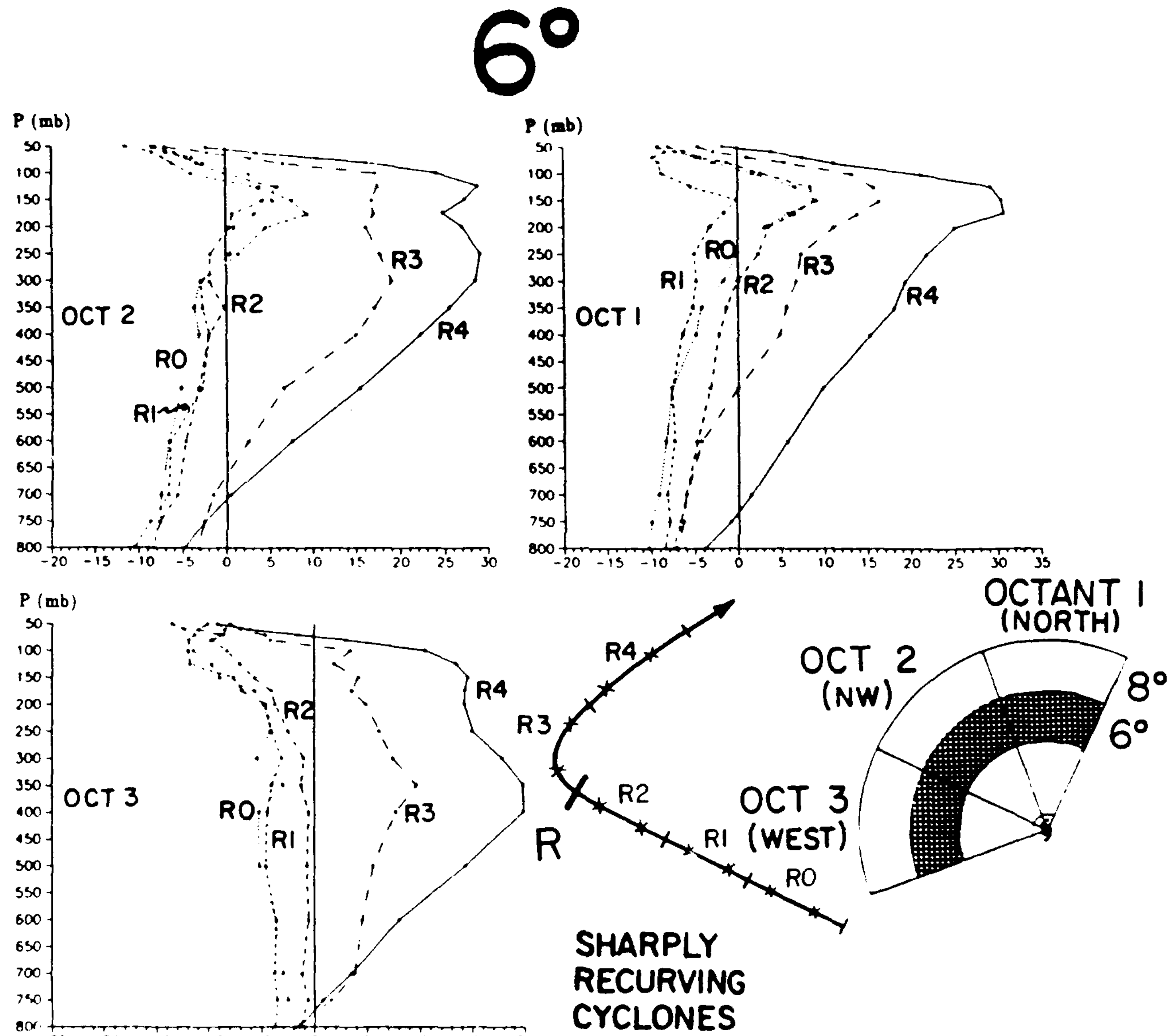


Figure 3.4: The 6° zonal wind profiles for the five sharply recurving time periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units in ms^{-1}.

(R0 and R1) show zonal winds are from an easterly component in the mid and lower troposphere and from a weak westerly component in the upper troposphere. Note that the profiles at this radius for these two time periods show characteristics similar to those of the non-recurving profiles (Fig. 3.3). At period R2, changes occur at 8° which are similar to those which occurred between periods R2 and R3 at 6°. Mid and upper tropospheric zonal winds in octants 1 and 2 at 8° shift from an easterly component to westerly component between periods R1 and R2 (Table 3.6). Note that even though the zonal component of the wind is in excess of +10 ms^{-1} in the mid and upper troposphere at 8° radius at period R2, the cyclone did not change direction. Once the cyclones begin to recurve, the zonal profiles at 8° during periods R3 and R4 become increasingly sheared from the west.

Table 3.6: Zonal wind differences between sharply recurving time periods R2 and R1 (24h change), and R1 and R0 (24h change). The differences are taken at 8 degrees from the center of the cyclone in octants 1 and 2. Units in ms^{-1}.

	Sharply Recurving Cyclones Zonal Wind Differences—8 Degrees			
	Octant 2 (Northwest)		Octant 1 (North)	
P (mb)	R2–R1	R1–R0	R2–R1	R1–R0
100	4.6	3.2	12.7	3.9
150	7.9	-0.2	12.6	6.9
200	12.8	-5.1	16.5	4.4
250	8.2	-0.4	18.8	1.2
300	18.0	-3.1	10.7	3.2
350	15.2	-2.6	9.3	3.5
400	12.3	-0.3	8.2	3.3
500	9.2	-1.6	5.7	2.8
600	4.9	-1.3	2.5	1.3
700	4.5	-3.1	-0.7	1.2
800	4.7	-4.0	-1.0	0.8

SUMMARY

The sharply recurving cyclones did not begin to recurve until positive zonal winds penetrated the mid troposphere to within 6° from the cyclone center in octants 1, 2 and

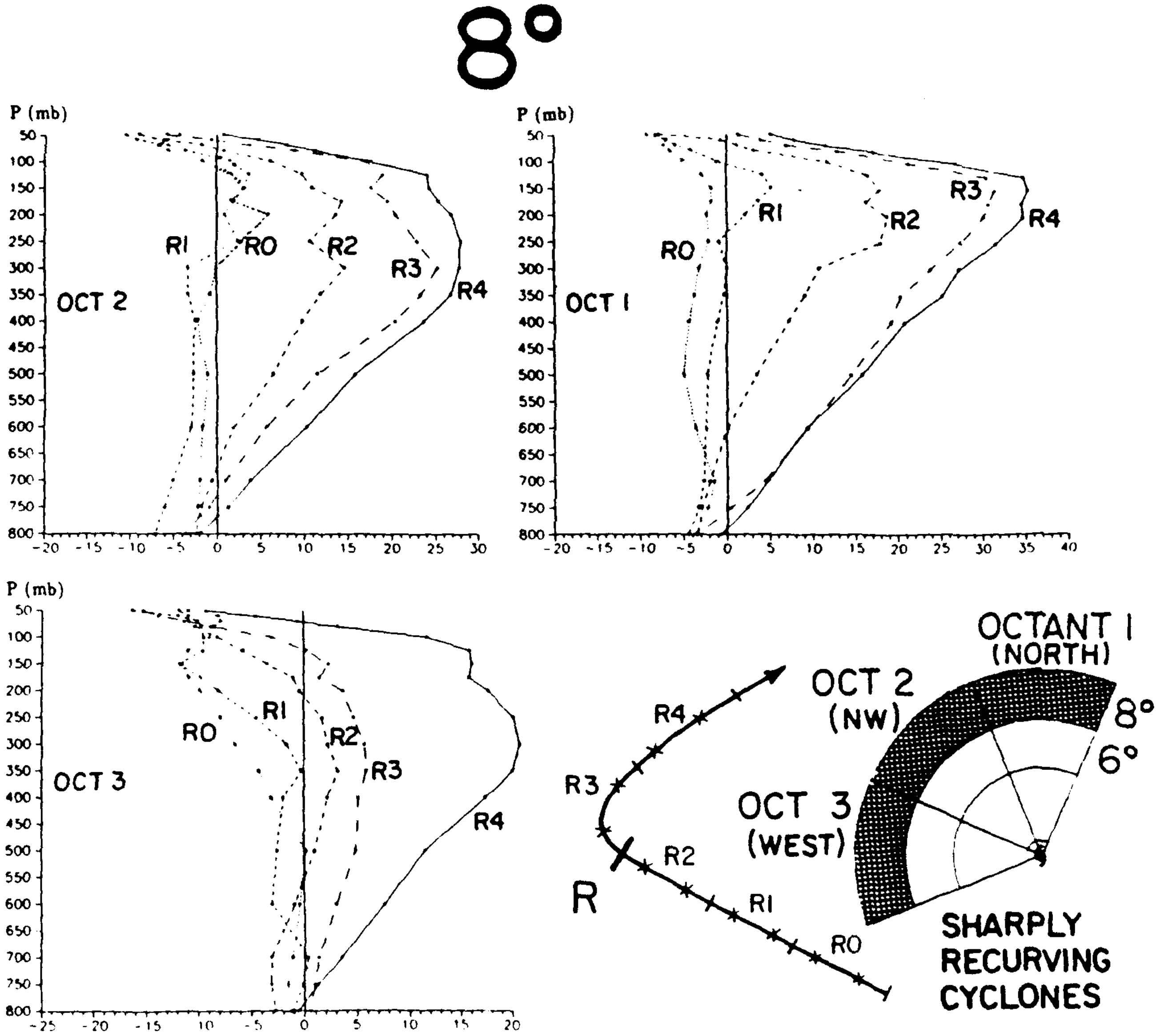


Figure 3.5: The 8° zonal wind profiles for the five sharply recurving time periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units in ms^{-1}.

3. Prior to the beginning of sharp recurvature, the zonal wind profiles at 6° in all three octants were similar to the non-recurving zonal wind profiles (except for the positive zonal winds in the upper troposphere).

Zonal wind profiles at 8° showed that significant changes in the environmental wind fields could occur with no immediate effect on the motion of the cyclone. Such changes in the wind fields are important for two reasons: 1) they exemplify the fact that positive zonal winds must reach to within 6° before the cyclone actually begins to recurve and, 2) significant changes in the zonal wind fields at 8° radius might signify that the cyclone is likely to begin recurving within the next 24 hours. Prior to period R2, 8° zonal profiles in octants 1 and 2 were similar to the non-recurving 8° zonal profiles. Between periods R2 and R1, the zonal winds at this location changed significantly, and immediately after period R2, the cyclones began to recurve sharply. These changes might signify that for a cyclone to begin recurving, mid and upper tropospheric zonal winds at 8° must shift from easterly to westerly components 12-24 hours prior to beginning recurvature. If the zonal winds at 8° radius can be measured accurately, they could be used to forewarn that sharp recurvature might begin in the near future.

As mentioned earlier, sharply recurving cyclones tended to show westerly winds in the upper troposphere up to 72 hours prior to beginning recurvature at both 6 and 8°. The most likely explanation of these westerlies is seasonal climatology; tropical cyclones which recurved sharply tended to occur during the months of September through November (see Table 2.1). Cyclones which move west during these months are more likely to encounter westerlies in the upper troposphere to the north and northwest simply because the mid-latitude westerly wind regime has moved farther equatorward during this time of the year. In addition, Guard (1977) showed that cyclones which recurved during the "winter season", showed direct links between the upper tropospheric outflow and the mid latitude westerly wind regime as much as 72 hours prior to recurvature; however it was also shown that not all cyclones which had a direct link to the westerlies recurved. As was shown in Figs. 3.4 and 3.5, tropical cyclones which recurved sharply encountered weak westerlies in the upper troposphere at 6° and 8° but did not begin to recurve until the westerlies penetrated the mid and upper troposphere to 6° from the cyclone's center.

3.2.3 Slowly Recurving Cyclones

Figure 3.6 and Fig. 3.7 show the 6° and 8° zonal wind profiles for the 6 slowly recurving time periods in octants 1, 2 and 3. Prior to the beginning of slow recurvature (periods SR1 and SR2), zonal profiles at 6° in octants 1, 2 and 3 [4] show winds from an easterly component throughout the troposphere. As the cyclones begin slow recurvature during period SR3, zonal winds in the mid and upper troposphere in octant 2 and mid troposphere in octant 3, shift from an easterly to a westerly component. However, zonal winds in octant 1 remain negative in nearly all levels of the troposphere. This change in the zonal wind fields between periods SR2 and SR3 is summarized in Table 3.7. As the cyclones continue to recurve during periods SR4, SR5 and SR6, zonal winds in the mid and upper troposphere in all 3 octants become positive and increase gradually in speed.

Table 3.7: *Slowly recurving zonal wind fields at 6 degrees at periods SR1, SR2 and SR3* in octants 2 and 3. Note how the zonal winds between periods SR2 and SR3 shift from an easterly to a westerly component.

	Octant 3 West		Octant 2 Northwest		
P (mb)	SR3	SR2	SR3	SR2	SR1
100	-11.0	-17.2	-5.6	-7.9	-13.0
150	-5.3	-9.5	2.3	-1.3	-4.7
200	-4.5	-7.8	1.8	-3.6	-9.4
250	-2.1	-5.4	0.7	-5.6	-14.1
300	-1.1	-4.3	0.9	-3.5	-11.2
350	0.3	-2.7	0.6	-5.4	-7.4
400	2.6	-3.1	0.5	-4.7	-8.4
500	3.3	-1.4	-1.5	-4.9	-7.1
600	2.9	-1.3	-2.8	-5.9	-7.2
700	4.0	-2.9	-2.8	-4.1	-11.2
800	2.5	-1.6	-4.4	-4.2	-11.8

[4] The data at period SR1 at 6 and 8° was limited to 2 - 5 observations in octants 1 and 2. No data was available at these radii in octant 3.

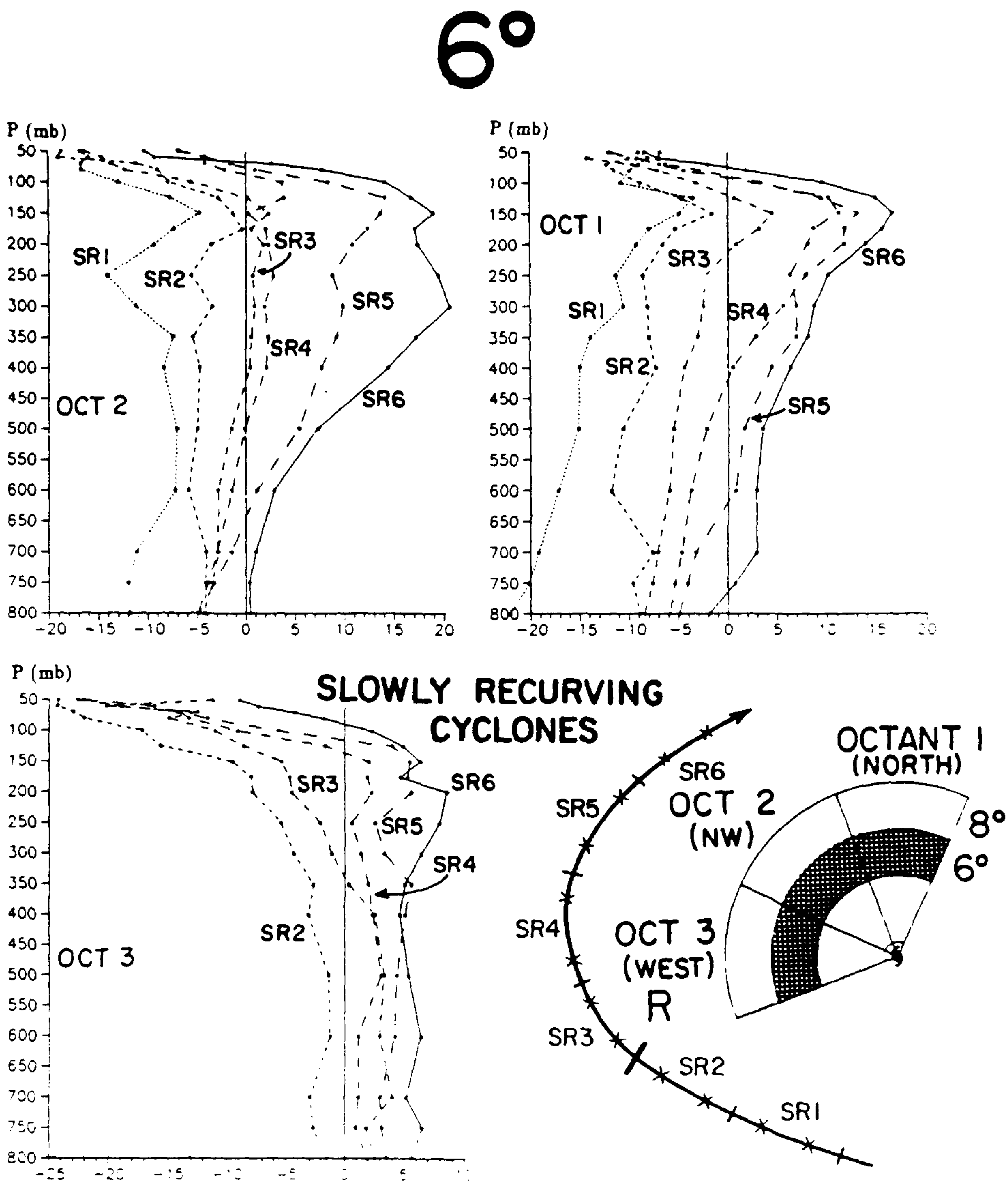


Figure 3.6: The 6° zonal wind profiles for the six slowly recurving time periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units in ms^{-1}.

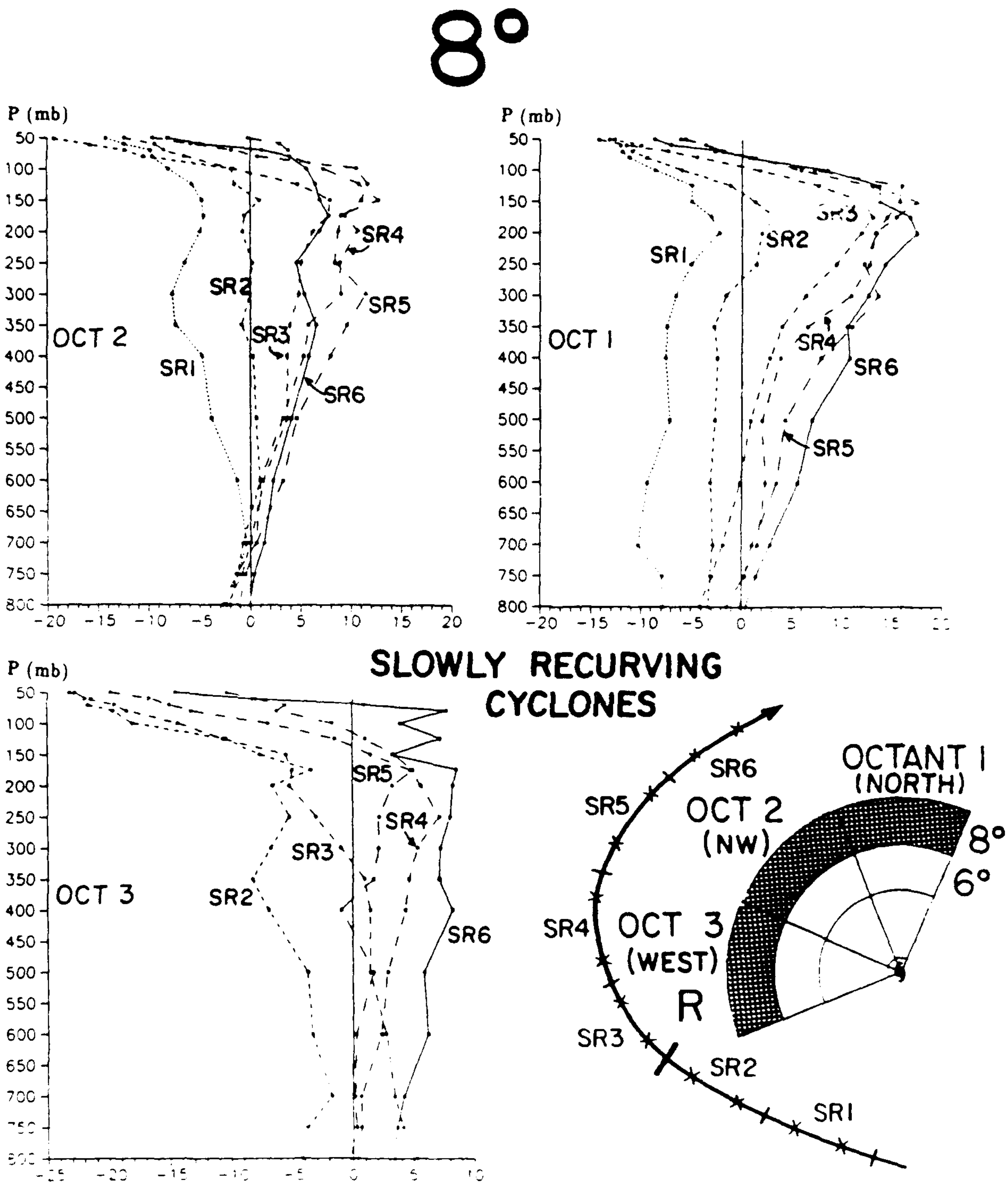


Figure 3.7: The 8° zonal wind profiles for the six slowly recurving time periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units in ms^{-1}.

The 8° zonal wind profiles for the 6 slowly recurving time periods are shown in Fig. 3.7. The zonal profiles for period SR1 are from an easterly component throughout the troposphere in octants 1 and 2. At period SR2, zonal winds in octants 1 and 3 are still from an easterly component throughout most of the troposphere, whereas zonal winds in octant 2 have become neutral throughout the troposphere. As the cyclones begin their slow recurvature during SR3, zonal winds in the mid and upper troposphere in octants 1 and 2 shift to westerly components while mid-tropospheric zonal winds in octant 3 also shift to a westerly component. As the cyclones continue to recurve to the north and northeast during the remaining three periods (SR4–SR6), zonal winds in all three octants become positive and gradually increase in speed throughout the troposphere.

SUMMARY

Slowly recurving cyclones did not begin to recurve until the zonal winds at 6° from the cyclones' center, shifted from easterly to weak westerly components through the mid and upper troposphere in octant 2 and the mid–troposphere in octant 3. Prior to beginning of slow recurvature, SR cyclones were embedded *in deep* easterly flow similar to that for non-recurving cyclones in all three octants.

Concerning advanced prediction of slow recurvature, zonal winds at 8° in octant 2 did show changes prior to beginning recurvature. During the first slowly recurving time period (SR1) zonal winds in octant 2 at 8° were from an easterly component at all levels in the troposphere. These zonal winds became neutral during period SR2. This weakness in the zonal component of the wind offers some forewarning that the cyclone might change course in the near future.

3.3 Comparisons of the Environmental Wind Fields of Sharply and Slowly Recurving Cyclones Prior to and after, Beginning Recurvature

The 6° and 8° zonal wind profiles in the previous section identified environmental characteristics which were related to non-recurving, slowly recurving and sharply recurving cyclones. It was shown that positive zonal winds had to penetrate the mid and upper troposphere to within 6° of the cyclones' center before the cyclone would begin recurvature.

It was also shown that positive zonal winds could penetrate the mid and upper troposphere at 8° and have no effect on the direction of motion of the cyclone.

Although both the sharply and slowly recurving cyclones began to recurve when positive zonal winds penetrated the 6° mid-troposphere region of the cyclone, obvious differences in the speed and location of these positive zonal winds were apparent. To show how zonal wind fields of the two recurving data sets differ from one another during same time periods, zonal wind profiles for slowly and sharply recurving, and non-recurving cyclones during period 1 (ie., R1, SR1, NR1), period 2 (R2, SR2, NR2) and period 3 (R3, SR3, NR3) in octants 1, 2 and 3 will be compared. Non-recurving cyclones are compared with the recurving cyclones for illustrative purposes only. The non-recurving cyclone time periods, NR1, NR2 and NR3, are not in any way related to an R point. In addition, the cyclone profiles stratified by direction (westward, northward and northeastward moving cyclones) are also shown for comparative purposes only.

3.3.1 Comparison of Northwest (Octant 2) Environmental Wind Fields

The 6 and 8° zonal wind profiles in octant 2 for westward, northward and northeastward moving cyclones are shown in Fig. 3.8a. It can be seen that zonal wind profiles of westward moving cyclones show very little vertical shear and the zonal winds at both 6 and 8° are from an easterly component at all levels in the troposphere. The zonal profiles for cyclones tracking northward and northeastward show considerable westerly shear and that zonal winds in e mid and upper troposphere are positive. Note that zonal winds shift from an easterly component to a westerly component below the 550 mb level.

The remaining zonal wind plots in Fig. 3.8a-d show 6 and 8° zonal wind profiles for sharply recurving, slowly recurving and non-recurving cyclones in octant 2 at periods 1 (b), 2 (c), and 3 (d). The 6° zonal profiles for sharply recurving and slowly recurving cyclones during periods 1 and 2 (Fig. 3.8b-c bottom) show characteristics similar to those of non-recurving and westward moving cyclones wherein the zonal winds for each profile are from an easterly component at all levels of the troposphere with the exception of upper troposphere for the sharply recurving cyclones (see section 3.2.2). The period 3, 6°

zonal wind profiles (Fig. 3.8d bottom) show that significant changes have occurred in the sharply recurving and slowly recurving cyclone zonal profiles for this time period. The sharply recurving R3 zonal profile has become strongly sheared to the west and winds are in excess of +15 ms^{-1} throughout the mid and upper troposphere. The slowly recurving SR3 zonal profile shows very little westerly shear but the zonal winds in the mid and upper troposphere have shifted from an easterly to a weak westerly component. This is a significant change as shown in Table 3.8 wherein cyclones which were moving on a west-northwest course, including the sharply recurving cyclones prior the R-point, were embedded in easterly flow at all levels in octant 2 at 6° while the cyclones which were moving on a course other then west-northwest show positive 6° zonal winds in the mid and upper troposphere.

The 8° zonal profiles for the sharply recurving and slowly recurving cyclones during period 1 (Fig. 3.8b, top) show characteristics which are associated with non-recurving and westward moving cyclones; profiles throughout most of the troposphere are from an easterly component and no significant vertical shear is evident. The period 2, 8° zonal profiles for the sharply recurving and slowly recurving cyclones (Fig. 3.8c, top) are quite different. The sharply recurving R2 zonal profile is strongly sheared from the west, and zonal winds are in excess of +10 ms^{-1} in the upper troposphere. Although the slowly recurving SR2 profile is not sheared, the zonal winds have become neutral throughout the troposphere. Both the sharply and slowly recurving cyclones are moving on a west-northwest course during period 2. However, 8° zonal profile of the sharply recurving cyclones resembles the north moving cyclone profile while the slowly recurving zonal profile seems to be a cross between west moving cyclones and the north moving cyclones; i.e. the profile is not sheared like north moving cyclones, but neither do the zonal winds in the profile bear any likeness to west moving or non-recurving cyclones.

The 8° zonal wind profile during period 3 (Fig. 3.8d, top) shows that the zonal profile for the sharply recurving cyclones has become sheared strongly from the west. The

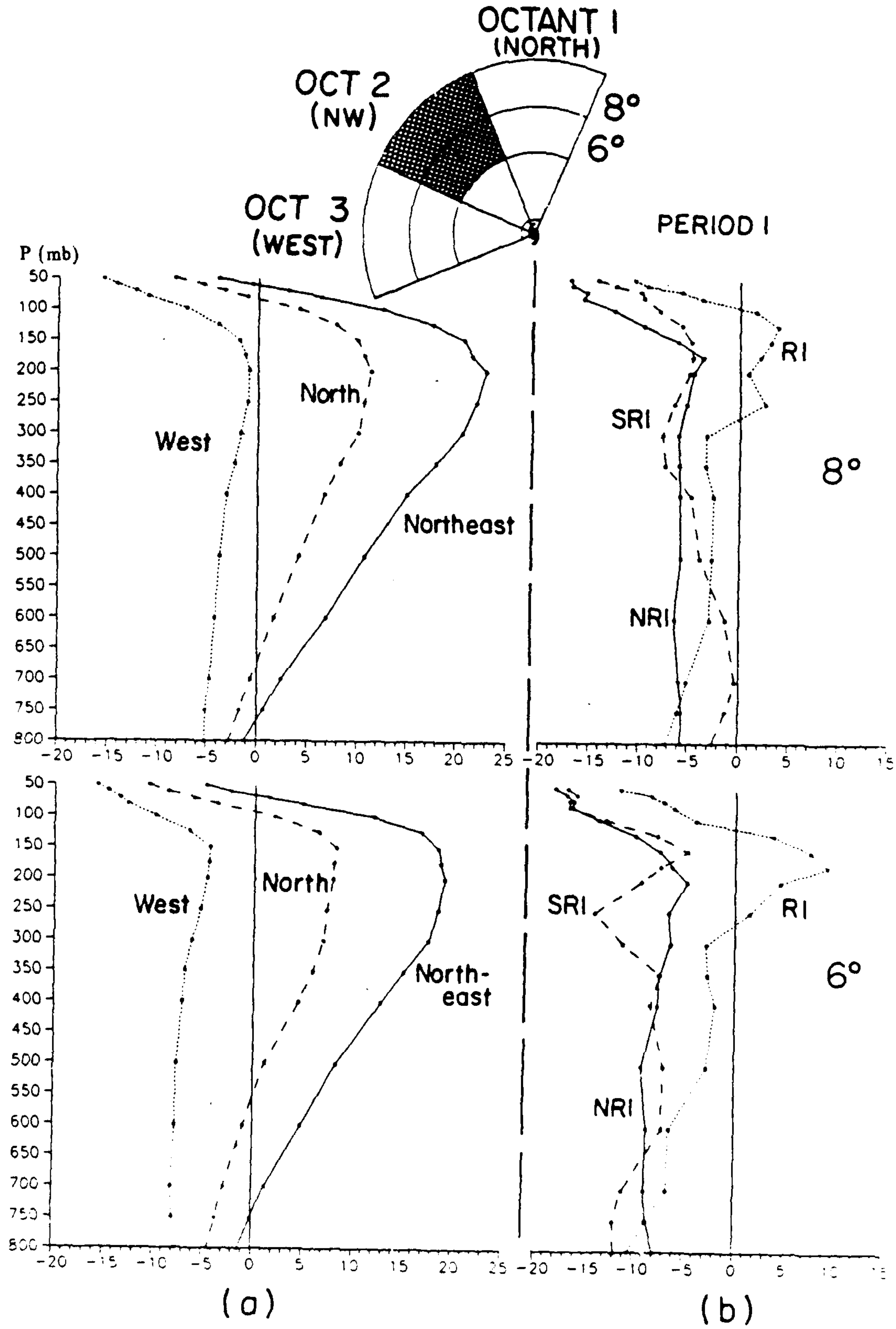


Figure 3.8: a-d. Octant 2, 8° (top) and 6° (bottom) zonal wind profiles of west, north and northeast moving cyclones (a) and the sharply recurving, slowly recurving, and non-recurving cyclones during period 1 (b), period 2 (c), and period 3 (d). Units in ms^{-1}.

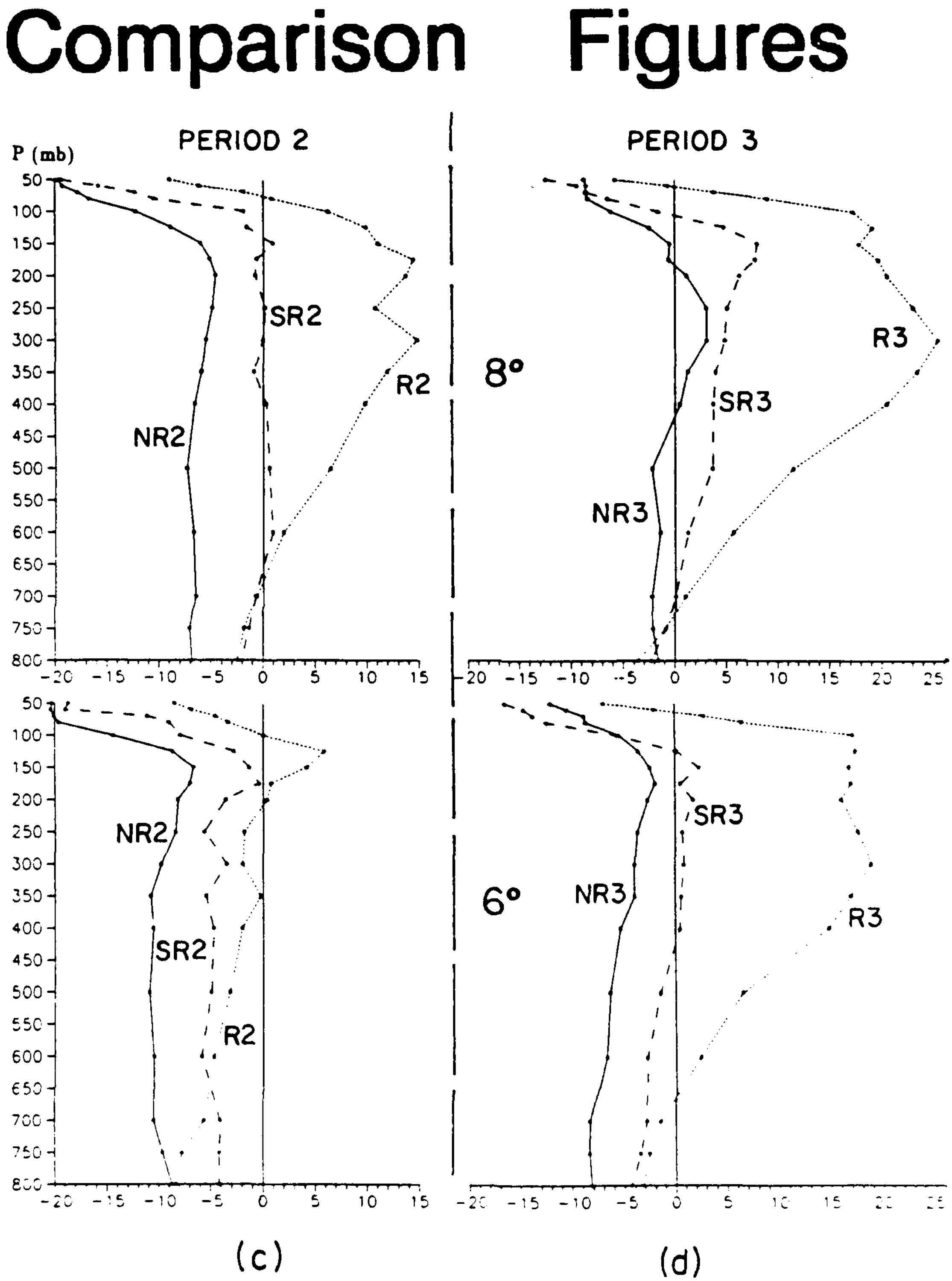


Figure 3.8: c-d. Continued.

Table 3.8: Zonal wind fields at 6 degrees in octant 2 (northwest) for cyclone–time periods moving west-northwest (top) and cyclone–time periods either recurving or moving north or northeast (bottom). See Table 2.3 for summary of cyclone directions. (The positive zonal winds during periods R1 and R2 were likely due to seasonal climatology and are not believed to be a precursor to sharp recurvature. See text for discussion.)

Octant 2 Zonal Winds—6 Degrees

	Sharply Recurving Cyclones Prior to Beginning Recurvature		Slowly Recurving Cyclones Prior to Beginning Recurvature		Non-recurving Cyclones			West Moving Cyclones
P (mb)	R2	R1	SR2	SR1	NR1	NR2	NR3	West
100	0.0	-3.9	-7.9	-13.0	-5.4	-14.4	-13.7	-10.1
150	4.2	7.6	-1.3	-4.7	-2.5	-6.7	-7.5	-4.4
200	0.4	4.5	-3.6	-9.4	-2.7	-8.1	-4.8	-4.7
250	-1.8	1.4	-5.6	-14.1	-5.7	-8.4	-6.6	-5.3
300	-1.9	-2.8	-3.5	-11.2	-4.0	-9.8	-6.5	-6.2
350	-0.2	-2.7	-5.4	-7.4	-4.0	-10.8	-7.5	-6.9
400	-2.0	-1.9	-4.7	-8.4	-5.3	-10.8	-7.7	-7.1
500	-3.2	-2.8	-4.9	-7.1	-6.4	-10.5	-9.3	-7.7
600	-4.7	-6.4	-5.9	-7.2	-6.7	-10.9	-8.8	-7.8
700	-5.6	-6.7	-4.1	-11.2	-8.3	-10.5	-8.9	-8.2
800	-8.4	-10.5	-4.2	-11.8	-8.2	-8.8	-7.9	-7.7

	Slowly Recurving Cyclones After Beginning Recurvature	Sharply Recurving Cyclones After Beginning Recurvature	North Moving Cyclones	Northeast Moving Cyclones
P (mb)	SR3	R3	NORTH	NORTHEAST
100	-5.6	17.1	2.0	11.9
150	2.3	16.8	8.2	18.4
200	1.8	16.0	7.9	19.1
250	0.7	17.6	7.3	18.5
300	0.9	18.9	7.0	17.5
350	0.6	16.9	5.9	15.1
400	0.5	14.8	4.5	12.7
500	-1.5	6.6	1.2	8.2
600	-2.8	2.4	-0.9	4.8
700	-2.8	-1.5	-2.8	1.3
800	-4.4	-3.2	-4.4	-1.4

zonal profile of the slowly recurving cyclones have also become sheared from the west with positive zonal winds existing throughout the mid and upper troposphere.

DISCUSSION

The mid tropospheric zonal winds at 6° in octant 2 are critical for differentiating between those cyclones which move on a west-northwest course versus those which begin recurving. Tropical cyclones which were moving on a west-northwest course (including both the sharply and slowly recurving cyclones prior to the beginning of recurvature) had negative zonal winds located throughout much of the troposphere at 6°. Cyclones which had begun to recurve, or were moving on a north or northeast course, had positive zonal winds located at nearly all levels within the troposphere. The zonal wind profiles at 8° showed that strong westerlies could reach to within 8° of the cyclone and yet, have no bearing on the direction of motion of the tropical cyclone, but as was shown in section 3.2, these changes at 8° could also forewarn that recurvature might occur in 12-24 hours.

3.3.2 Comparison of West (Octant 3) Environmental Wind Fields

The 6 and 8° zonal wind profiles for westward, northward and northeastward moving cyclones in octant 3 are shown in Fig. 3.9a. The primary differences among the westward, northward and northeastward moving cyclones are that the zonal winds of westward moving cyclones were from an easterly component throughout the troposphere whereas zonal winds of northward and northeastward moving cyclones were from a westerly component throughout the troposphere.

The remaining zonal wind plots in Fig. 3.9a-d show the 6 and 8° zonal wind profiles for the sharply recurving, slowly recurving and non-recurving cyclones in octant 3 at periods 1 (b), 2 (c), and 3 (d). The 6° zonal profiles for the sharply and slowly recurving cyclones during the first two time periods (Fig. 3.9b-c, bottom) are from an easterly component throughout the troposphere. This feature is characteristic of non-recurving and westward moving cyclones (Table 3.9). Once the sharply and slowly recurving cyclones begin to recurve during period 3 (Fig. 3.9d), the zonal profiles take on characteristics typical of northward moving cyclones; specifically, the zonal profiles become positive throughout the

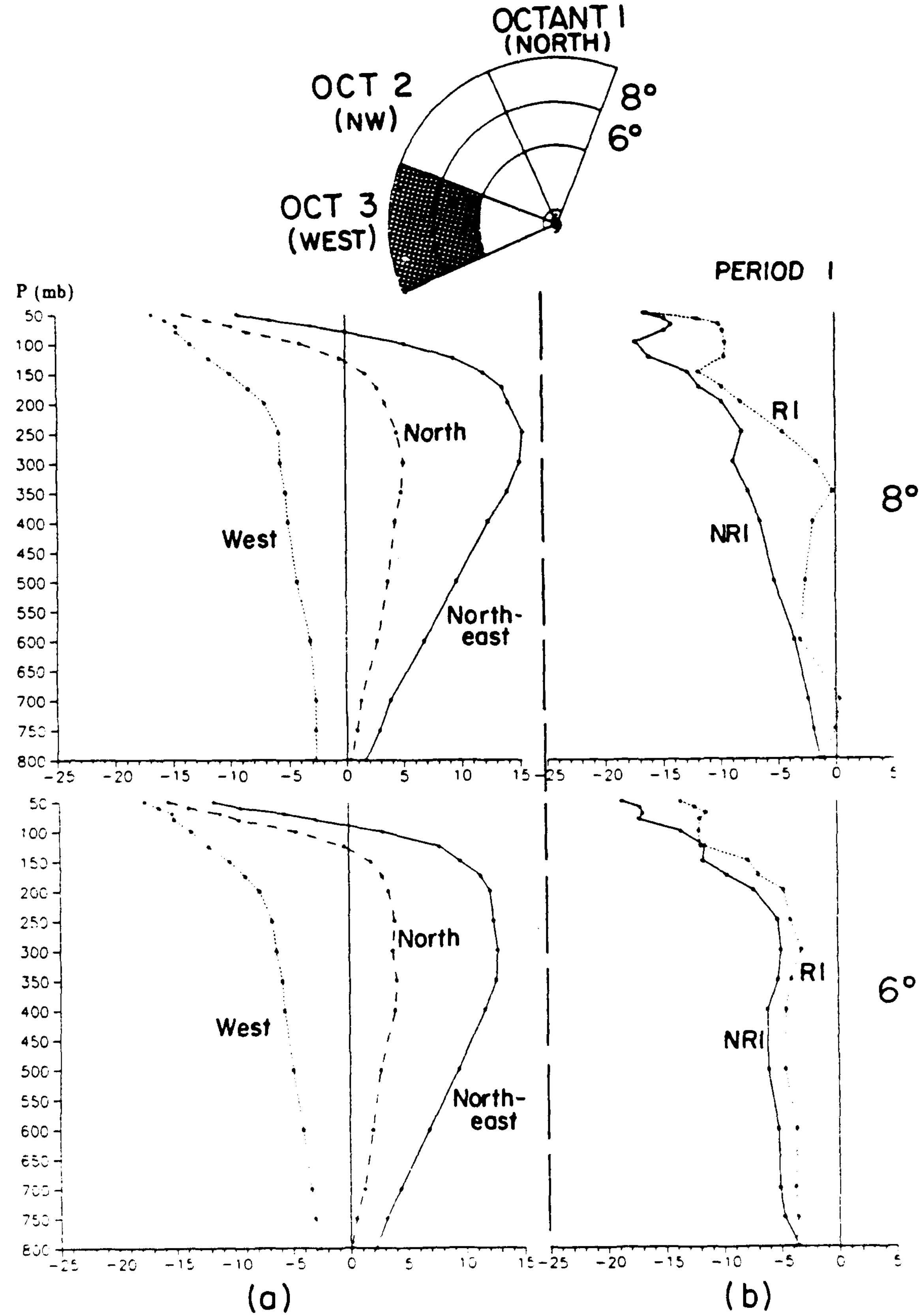


Figure 3.9: a-d. Octant 3, 8° (top) and 6° (bottom) zonal wind profiles of west, north and northeast moving cyclones (a) and the sharp recurving, slowly recurving, and non-recurving cyclones during period 1 (b), period 2 (c), and period 3 (d). Units in ms^{-1}.

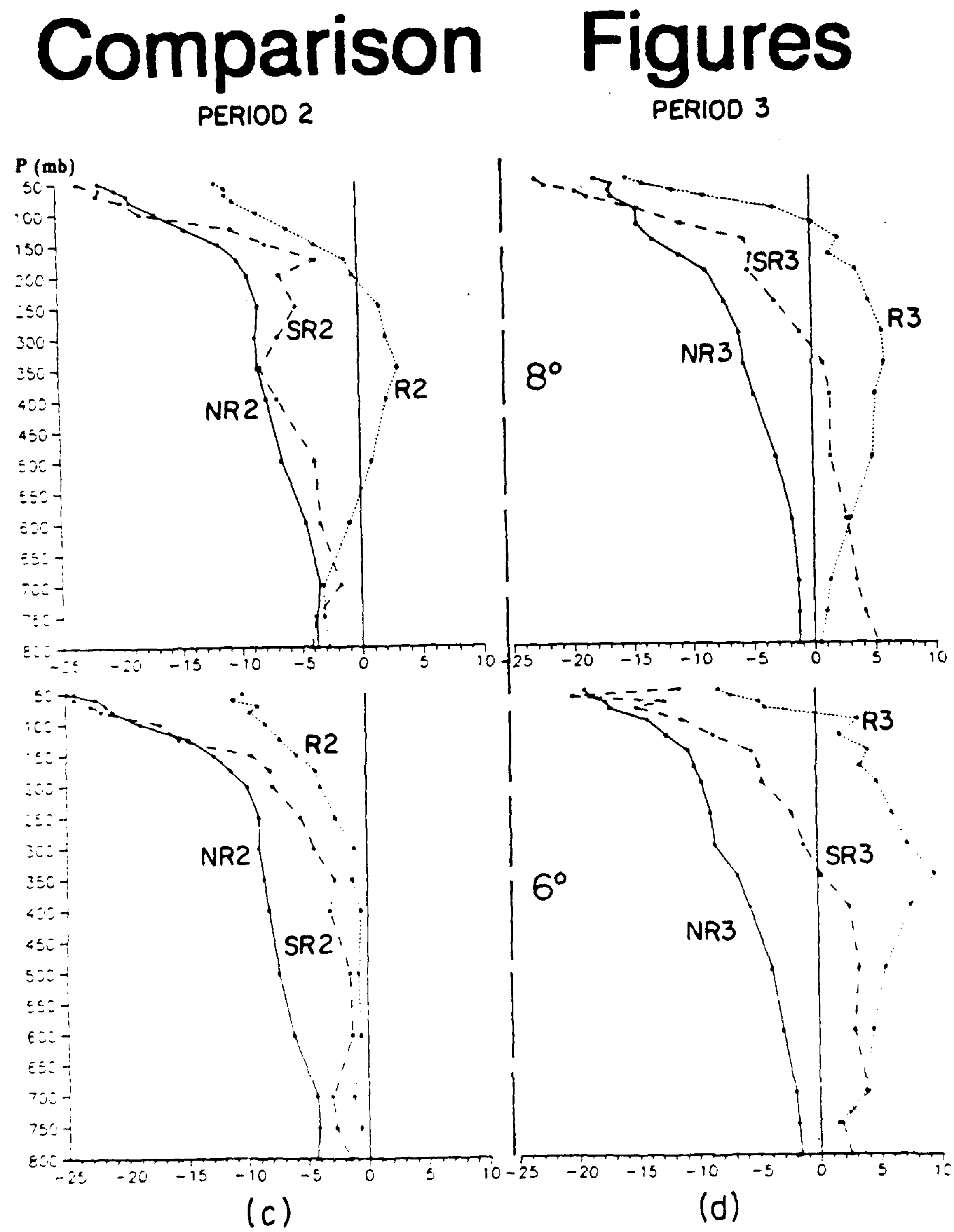


Figure 3.9: c-d. Continued.

troposphere for the sharply recurving cyclones while becoming positive only in the lower and mid troposphere for slowly recurving cyclones.

The 8° zonal profiles for the sharply recurving, slowly recurving and non-recurving cyclones during periods 1, 2 and 3 (Fig. 3.9b-d, top) are nearly identical to the 6 zonal profiles (Fig. 3.9b-d, bottom), with the important exception that the sharply recurving zonal profile at period 2 shows weak positive zonal winds in the mid troposphere.

DISCUSSION

The 6° zonal profiles in octant 3 indicated that zonal winds from an easterly component at all levels of the troposphere were characteristics of cyclones moving on a west-northwest course. If the zonal winds at 6° in this octant were from a westerly component, then cyclones were typically moving on a course other then west-northwest; i.e the cyclones were either recurving or moving north or northeast.

3.3.3 Comparison of the North (Octant 1) Environmental Wind Fields

Zonal wind profiles at 6 and 8° for the westward, northward and northeastward moving cyclones in octant 1 are shown in Fig. 3.10a. Although the zonal profiles of westward moving cyclones are somewhat sheared from the west, zonal winds are from an easterly component throughout the troposphere (except at 150 and 175 mb.) at 6°. Meanwhile at 8°, zonal winds in the upper and parts of the mid troposphere are from a weak westerly component. The zonal profiles of northward and northeastward moving cyclones show significant westerly shear with winds in the mid and upper troposphere from a westerly component. These westerly winds in the upper troposphere exceed 10 and 20 ms^{-1} for the northward and northeastward moving cyclones, respectively.

The remaining zonal wind plots in Fig. 3.10a-d show 6 and 8° zonal wind profiles for the sharply, slowly and non-recurving cyclones in octant 1 at periods 1 (b), 2 (c), and 3 (d). The 6° zonal profiles for sharply and slowly recurving cyclones for period 1 (Fig. 3.10b-c, bottom) are similar to those of non-recurving and westward moving cyclones wherein each profile shows easterly zonal winds in the mid-troposphere. The 6° zonal profiles for the slowly recurving cyclones at period 2 (Fig. 3.10b-c, bottom) remain similar to the

Table 3.9: Zonal wind fields at 6 degrees in octant 3 (west) for time periods of west-northwest motion (top) and time periods of either recurving or north or northeast motion (bottom).

Octant 3 Zonal Winds—6 Degrees

	Sharply Recurving Cyclones Prior to Beginning Recurvature		Slowly Recurving Cyclones Prior to Beginning Recurvature	Non-recurving Cyclones			West Moving Cyclones
P (mb)	R2	R1	SR2	NR3	NR2	NR1	West
100	-8.3	-12.0	-17.2	-13.9	-18.8	-13.6	-13.6
150	-5.7	-7.8	-9.5	-10.6	-12.7	-11.7	-10.3
200	-3.8	-4.7	-7.8	-9.5	-9.9	-7.3	-7.7
250	-2.5	-4.1	-5.4	-8.8	-8.9	-5.2	-6.6
300	-1.0	-3.1	-4.3	-8.4	-9.0	-4.9	-6.3
350	-1.3	-4.1	-2.7	-6.6	-8.6	-5.2	-5.8
400	-0.6	-4.5	-3.1	-5.6	-8.2	-6.1	-5.6
500	-0.7	-4.6	-1.4	-3.8	-7.3	-6.1	-4.9
600	-0.6	-3.6	-1.3	-3.0	-6.1	-5.2	-4.0
700	-1.2	-3.8	-2.9	-2.0	-4.2	-5.1	-3.4
800	-1.4	-3.7	-1.6	-1.6	-4.3	-3.5	-2.7

	Slowly Recurving Cyclones After Beginning Recurvature	Sharply Recurving Cyclones After Beginning Recurvature	North Moving Cyclones	Northeast Moving Cyclones
P (mb)	SR3	R3	NORTH	NORTHEAST
100	-11.0	3.5	-4.5	3.0
150	-5.3	4.2	1.9	9.6
200	-4.5	4.9	3.4	12.1
250	-2.1	6.2	4.0	12.4
300	-1.1	7.4	3.8	12.8
350	0.3	9.7	4.1	12.6
400	2.6	7.7	4.0	11.7
500	3.3	5.5	2.7	9.4
600	2.9	4.5	2.0	6.9
700	4.0	3.8	1.2	4.4
800	2.5	-1.8	-0.1	2.2

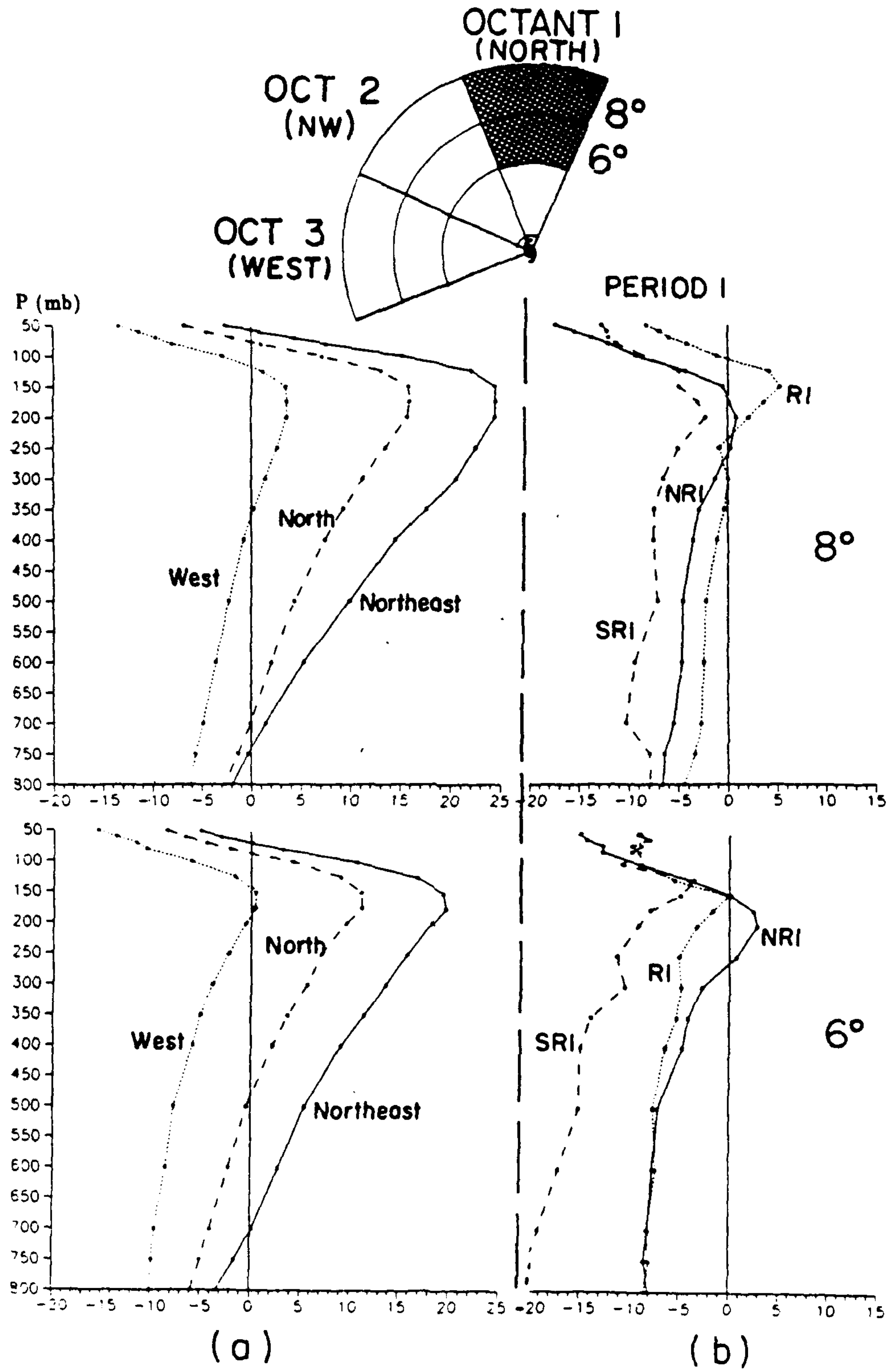


Figure 3.10: a-d. Octant 1, 8° (top) and 6° (bottom) zonal wind profiles of west, north and northeast moving cyclones (a) and the sharply recurving, slowly recurving, and non-recurving cyclones during period 1 (b), period 2 (c), and period 3 (d). Units in ms^{-1}.

Comparison Figures

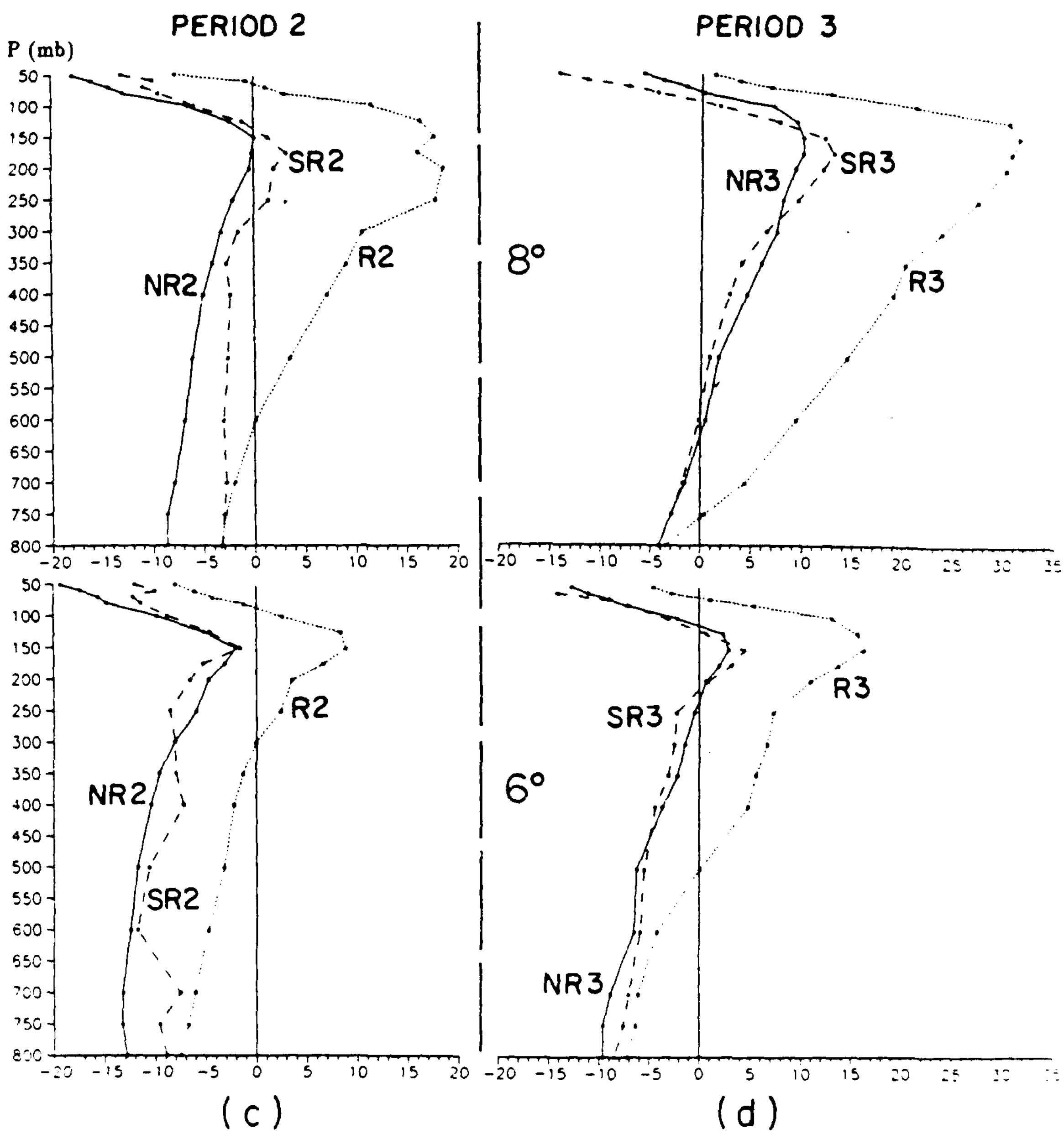


Figure 3.10: c-d. Continued.

non-recurving and westward moving cyclones. However, the sharply recurving cyclone profile at this time period has become sheared from the west. Note that zonal winds below 300 mb for period R2 are still from an easterly component. The 6° zonal profiles at period 3 (Fig. 3.10d) show positive zonal winds have penetrated into the mid and upper troposphere of the sharp recurving profile. The slowly recurving cyclone profile on the other hand has not changed significantly from the previous two time periods. Even though the slowly recurving cyclones have begun to recurve during this period, the SR3 zonal profile is nearly identical to the non-recurving and west moving cyclone profiles.

The 8° zonal profiles for the sharply, slowly and non-recurving cyclones at period 1 (Fig. 3.10b, top) show zonal winds from an easterly component throughout a majority of the troposphere at this time. The 8° zonal profiles at period 2 (Fig. 3.10c) show that the slowly recurving and non-recurving cyclones still resemble the west moving cyclone zonal profile, but that the sharply recurving cyclone profile has become strongly sheared and resembles the north moving cyclone profile. The 8° zonal profiles for period 3 show that the sharply recurving profile is strongly sheared and resembles the zonal profile for northeast moving cyclones, while the slow recurving profile has also become sheared from the west.

DISCUSSION

Similar to the zonal profiles in octant 2, the zonal wind profiles in octant 1 show that the sharply recurving cyclones do not begin to recurve until the westerlies penetrate the mid troposphere at 6° in octant 1. The same cannot be said of the slowly recurving cyclones wherein the zonal wind profiles during this time were similar to those of the west moving and non-recurving cyclone profiles.

It is interesting to note the 6° zonal wind profiles of the slow and non-recurving cyclones for period 3 in octant 1 are, nearly identical (Fig. 3.10d). Since it is known that during period 3, non-recurving cyclones are moving west-northwest while slowly recurving cyclones are recurving off to the north-northwest, why then did the slowly recurving cyclones begin to recurve when the zonal profiles for both in octant 1 were nearly identical?

This question can be answered by comparing the period 3 zonal profiles in octants 2 and 3. Figure 3.11 shows the slow, sharp and non-recurving 6° zonal wind profiles in octants 1, 2 and 3 at period 3. As was shown earlier, the slowly recurving cyclones are identical to the non-recurving zonal profile in octant 1. The zonal profiles in the octants 2 and 3 though, are quite different. The 6° zonal profiles of the non-recurving cyclones show the zonal winds remain from an easterly component in both octants 2 and 3. The 6° zonal profiles of the slowly recurving cyclones show that positive zonal winds have penetrated into the mid and upper troposphere in octant 2 and in the mid and lower troposphere in octant 3. It is more than likely that the penetration of positive zonal winds into the mid troposphere at 6° in octants 2 and 3 allow the cyclones to actually begin to slowly recurve.

3.4 Summary of Sharply Recurving, Slowly Recurving and Non-Recurving Cyclones

The environmental wind fields at 6° in octants 2 and 3 are critical for differentiating between non-recurvature and beginning recurvature. The cyclones which were moving west-northwest (the non-recurving cyclones, the west moving cyclones and the sharply recurving and slowly recurving cyclones prior to beginning recurvature) all had one feature in common; the zonal winds in the mid and upper troposphere in octants 2 and 3 were from an easterly component. The cyclones which had begun to recurve or were moving on a course other then west-northwest (sharply recurving and slowly recurving cyclones after beginning recurvature, and the north and northeast moving cyclones) all had positive zonal winds located in the mid troposphere at these locations.

The 6° zonal profiles also identified characteristics which differentiated the beginning of sharp recurvature from the beginning of slow recurvature. A tropical cyclone would begin sharp recurvature when positive zonal winds penetrated the mid and upper troposphere 6° to the west, northwest and north of the cyclone. Tropical cyclones would begin slow recurvature when weak positive zonal winds penetrated into the mid and upper troposphere in octants 2, and the mid troposphere in octant 3.

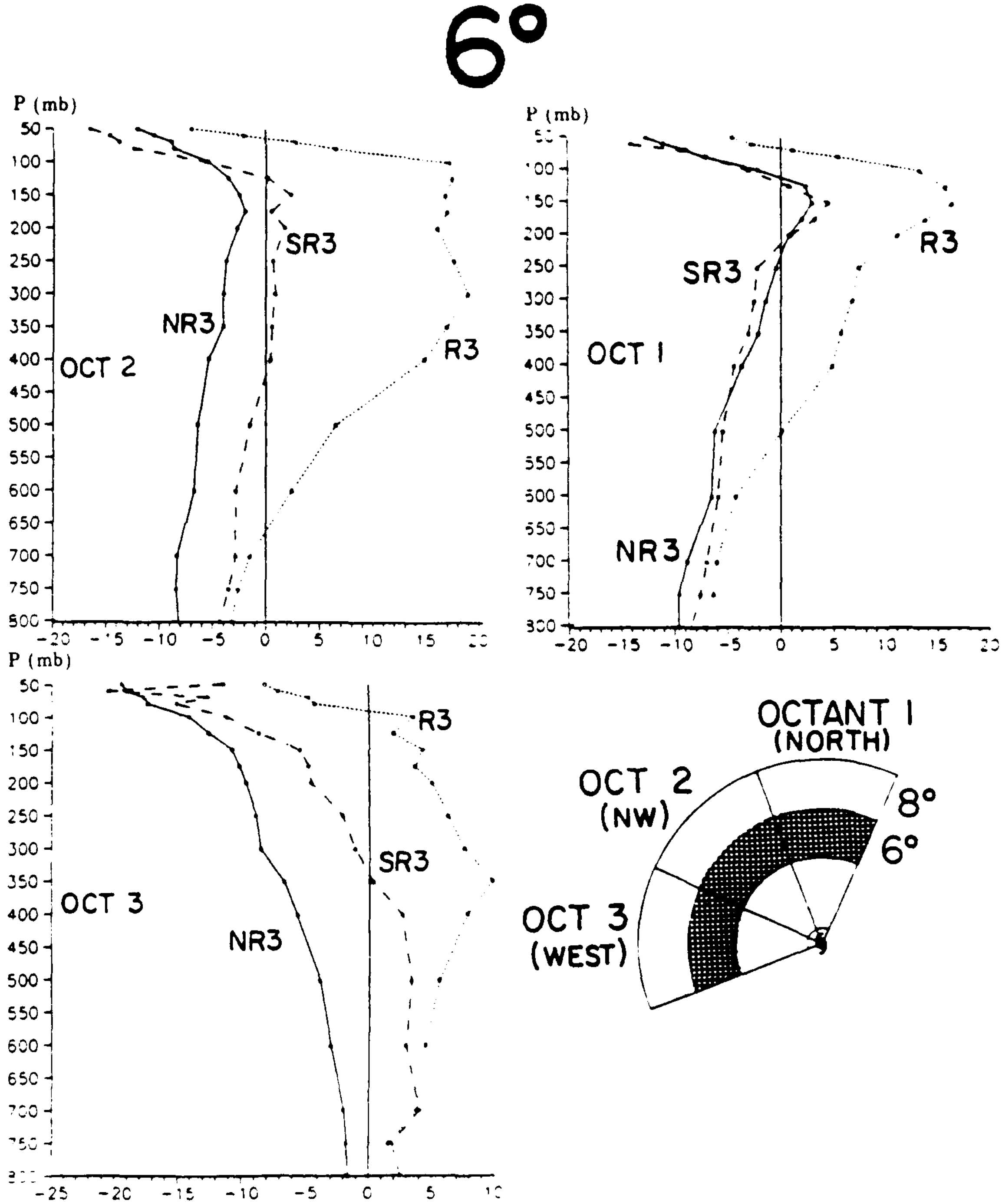


Figure 3.11: The 6° zonal wind profiles of the sharply recurving, slowly recurving, and non-recurving cyclones in octants 1 (upper right), 2 (upper left) and 3 (lower left) at period 3. Units in ms^{-1}.

The zonal wind fields 8° were found to be important for identifying tropical cyclones which might potentially recurve. Prior to beginning sharp recurvature, the mid and upper tropospheric zonal winds in octants 1 and 2 changed from an easterly component to a westerly component. This same change was found for the slowly recurving cyclones, except the zonal winds changed from easterly to neutral in octant 2.

The following list summarizes the conditions which are necessary for a west-northwest moving cyclone to begin recurving:

- A tropical cyclone will remain on a west-northwest course for at least the next 36 hours if the zonal winds in the mid troposphere, 8° to the north, northwest, and west of the storm's center, are from an easterly component, and the zonal winds in the upper troposphere do not exceed +5 ms^{-1}.

- A tropical cyclone could be expected to begin SHARP recurvature in the next 12 hours if the zonal winds in the mid and upper troposphere, 8° to the north and northwest of the storms' center, shift from an easterly component to a westerly component (> 10 ms^{-1}).

- A tropical cyclone could be expected to begin SLOW recurvature in the next 12 hours if the zonal winds 8° to the northwest of the storm's center are shifted from a easterly component to a weak westerly component, or become neutral, throughout the mid and upper troposphere.

- A tropical cyclone will actually begin SHARP recurvature when the zonal winds in the mid and upper troposphere, 6° to the north, northwest and west of the storms' center, shift from an easterly component to a westerly component.

- A tropical cyclone will actually begin SLOW recurvature when the zonal winds in the mid troposphere, 6° to the northwest and west of the storms' center, shift from an easterly component to a westerly component.

An additional characteristic of both sharply recurving and slowly recurving cyclones is: If the 200-500 mb layer average zonal wind component 6° to the northwest of the cyclone is from the east, then the cyclone will move on a west-northwest course; if these winds are from the west, the cyclone has already begun to recurve. Figure 3.12 shows the 200-500 mb zonal average winds at 6 and 8° for the sharply recurving, slowly recurving and non-recurving cyclones at periods 1, 2 and 3. As can be seen, the 200-500 mb layer zonal average flow at 6° for the sharply recurving and slowly recurving cyclones prior to beginning recurvature was from an easterly component. Once both the slowly recurving and sharply recurving cyclones began to recurve, the layer average zonal component shifted to the west. It is important to note that this same rule does not work at 8°.

3.5 Environmental Characteristics Associated with Left Turning Cyclones

Until now, most of the tropical cyclone discussion has dealt with cyclones turning to the right of their previous west-northwest track. In this section, zonal (u) and total wind profiles (u + v) will be employed to show how the environmental wind fields associated with a north-northwestward moving cyclone change with time to allow the cyclone to resume a west-northwest course.

Figure 3.13 show the 6° zonal wind profiles for the four left turning time periods (L3–L6) in octants 1, 2 and 3. The 6° zonal wind profiles in octant 1 (Fig. 3.13) are similar to each other, but important differences do exist in the upper troposphere. Note the pressure level where the zonal wind shifts from an easterly component to a westerly component. During time periods L3 and L4 when the cyclones were moving slowly north-northwest, the changeover from east to west occurs at ~375 mb and 350 mb respectively; as the cyclone turned to the left and resumed a west-northwest track (periods L5 and L6) the changeover occurred higher up, at the ~ 300 and 250 mb levels respectively. The zonal wind profiles in octant 2 show that positive zonal winds exist in the upper troposphere during three of the four time periods, but these positive zonal winds are weak (< ~5 ms^{-1}) and are believed to play no significant role in the north to west direction change. Zonal profiles in octant 3 show that zonal winds at 6° changed considerably during each of the four left turning time periods. The zonal winds at period L3 are negative throughout the mid and lower troposphere, but were strongly sheared above the 350 mb level, going

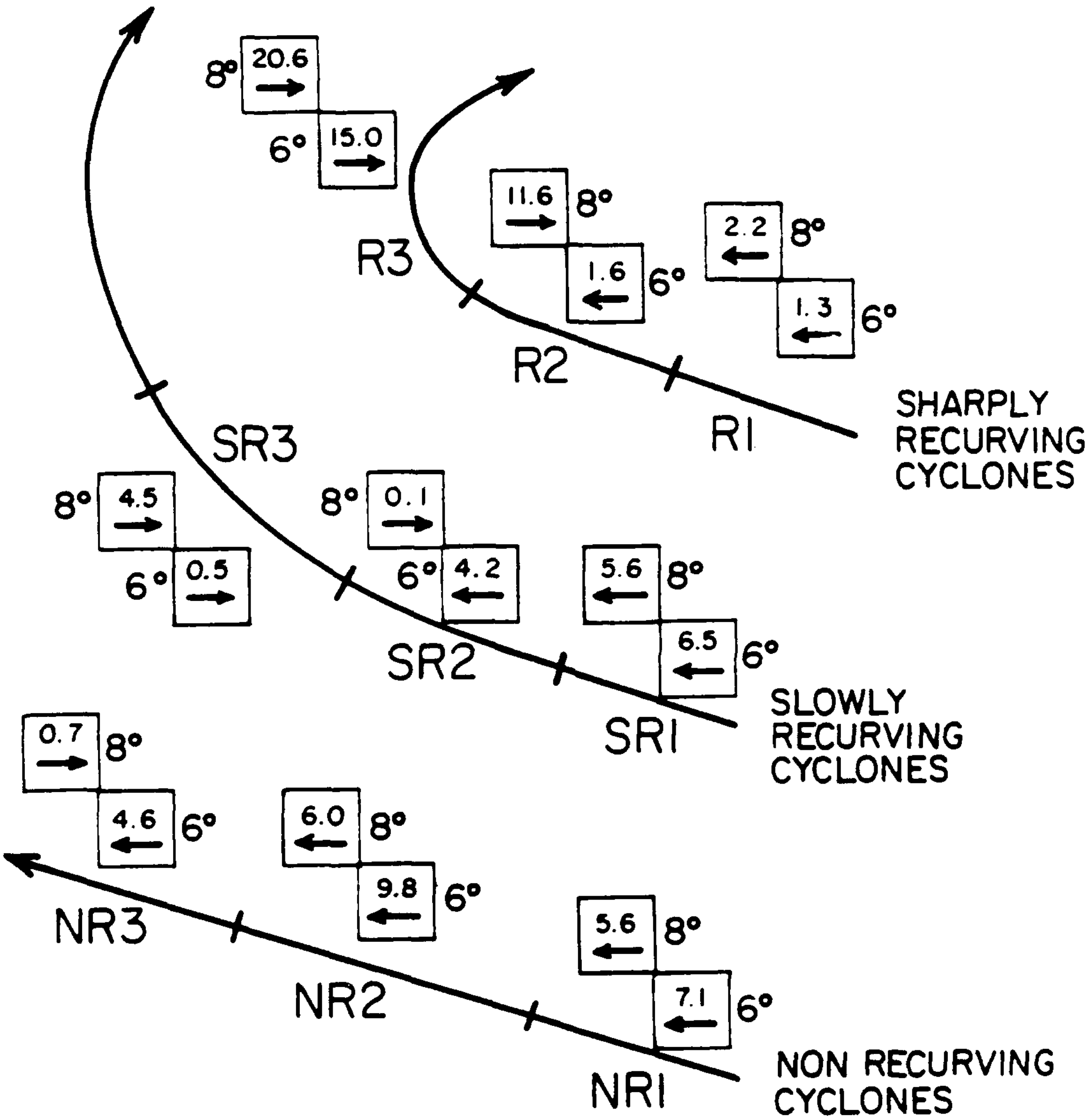


Figure 3.12: 200-500 mb layer average zonal winds at 6 and 8° in octant 2 for the sharply recurving (top), slowly recurving (middle), and non-recurving (bottom) cyclones at periods 1, 2, and 3. The arrow in each box represents direction. The small number above the arrow represents speed (ms^{-1}).

from -11 ms^{-1} at 350 mb to +4 ms^{-1} at the 200 mb level. The L4 zonal profile shows that the winds in the mid and upper troposphere shifted from an easterly component to a westerly component between period L3 and L4. As shown in Table 3.10, the zonal wind differences between period L4 and L3 show +11 ms^{-1} change at 350 mb, +7 ms^{-1} at 500 mb, and +10 ms^{-1} at 175 mb. As the cyclones turn back towards the west-northwest during period L5, the zonal winds shift back to an easterly component once again, with only weak westerlies at the 200 mb level. The L6 zonal profile shows that the zonal winds at all levels, including the upper troposphere, are from an easterly component throughout.

Figure 3.14 shows zonal wind profiles at 8° for the four left turning time periods in octants 1, 2 and 3. The 8° zonal wind profiles in octant 1 are nearly identical to each other, each profile showing weak easterlies below the 500 mb level. Above this level, zonal winds become positive and are sheared from the west. Zonal winds in octant 2 show very little shear in the vertical. The four left turning zonal profiles in octant 3 are similar to each other, except in the upper troposphere. When the cyclones are moving north, periods L3 and L4, the zonal profiles are sheared from the west above the 250 mb level. Once the cyclones return to a west-northwest course, (L5 and L6) shear in the upper troposphere dissipates.

To get a better picture of why the left turning cyclones moved north and then turned to the left, vector wind profiles (u + v) for the four left turning time periods in octant 1 are shown (Fig. 3.15a-d). The period L3 wind profiles (Fig. 3.15a) show strong west to southwest winds in the upper troposphere at 6 and 8°; westerly winds are in excess of 20 ms^{-1} at the 150 to 200 mb layer at 8°. What is most unusual about these profiles is the westerly winds do not continue to increase in speed with distance from the cyclone, but they decrease dramatically in speed and even shift back to easterlies through a majority of the upper troposphere at 10°. Beyond 10°, the mid and upper tropospheric westerlies return, but they are generally weak, ranging from 5 to 10 ms^{-1}. As shown in Fig. 3.16, the anonymously strong westerly winds at 6 and 8° are believed to be associated with

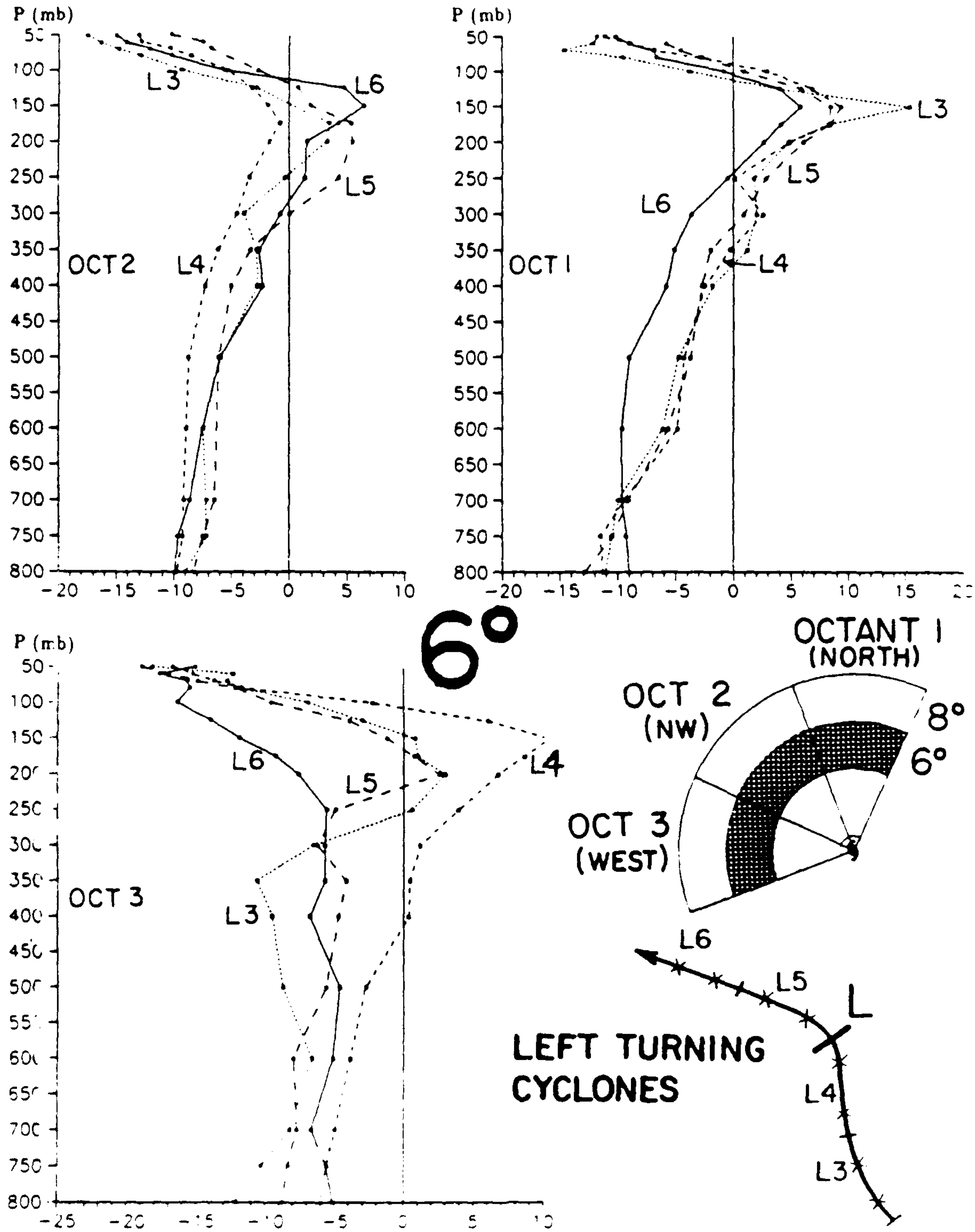


Figure 3.13: The 6° zonal wind profiles for the 4 left turning cyclone time periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units in ms^{-1}.

Table 3.10: Zonal winds (top) and zonal wind differences (bottom) at 6 degrees to the west (octant 3) of the 4 left turning cyclone time periods.

Zonal Winds Octant 3 (West) - 6°				
	L3	L4	L5	L6
P (mb)				
100	-6.9	-2.2	-9.6	-16.4
150	0.9	10.4	-1.2	-11.9
200	3.0	6.8	2.6	-7.6
250	0.6	3.9	-5.0	-5.6
300	-6.6	1.2	-6.3	-5.7
350	-10.6	0.4	-4.2	-5.7
400	-9.5	0.4	-4.7	-6.8
500	-8.7	-2.8	-5.6	-4.6
600	-6.6	-3.9	-8.0	-5.1
700	-8.3	-5.0	-7.7	-6.7
800	-12.2	-6.0	-8.8	-5.2

Zonal Wind Differences			
	L4 minus L3	L5 minus L4	L6 minus L5
P (mb)			
100	4.7	-7.4	-6.8
150	9.5	-11.6	-10.7
200	3.8	-4.2	-10.2
250	3.3	-8.9	-0.6
300	7.8	-7.5	0.6
350	11.0	-4.6	-1.5
400	9.9	-5.1	-2.1
500	5.9	-2.8	1.0
600	2.7	-4.1	2.9
700	3.3	-2.7	1.0
800	6.2	-2.8	3.6

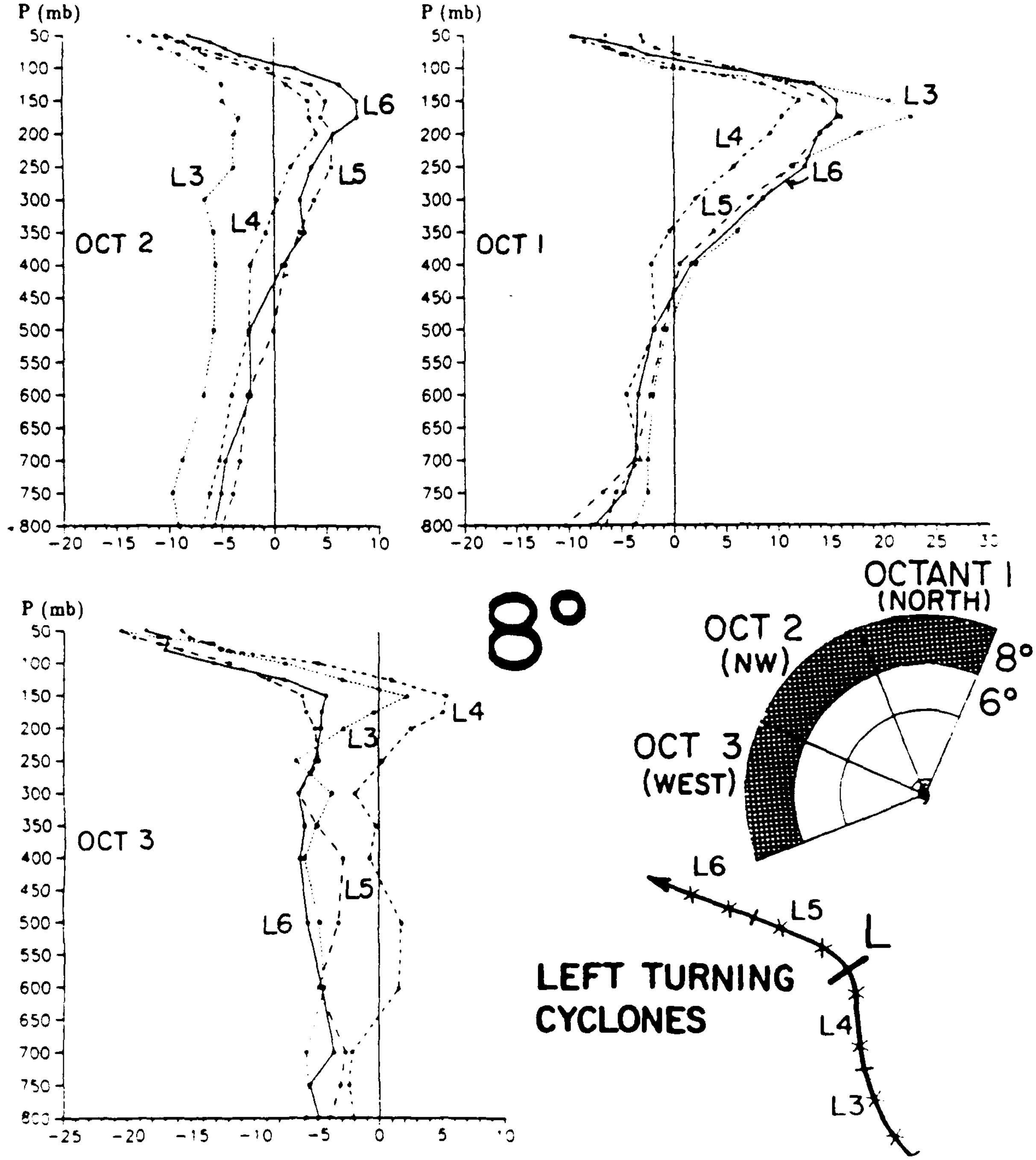


Figure 3.14: The 8° zonal wind profiles for the 4 left turning cyclone time periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units in ms^{-1}.

an tropical upper-tropospheric trough (TUTT), or an upper tropospheric trough of mid-latitude origin.

The period L4 wind profiles (Fig. 3.15b) in octant 1 show that the upper tropospheric westerlies at 6 and 8° have decreased in speed, while the easterlies which were previously located at 10° at period L3 have shifted to westerlies. Note that the upper level circulation which was present at period L3 is no longer visible in the wind fields at period L4. What is believed to have happened to the upper tropospheric trough is that it has either moved off towards the northeast, or it has weakened.

The period L5 wind profiles in octant 1 (Fig. 3.15c) show the upper tropospheric westerly winds at 6° continuing to weaken. In addition, the winds at this radius, specifically between the 300-500 mb layer have backed with time. The west winds at 8° have increased in speed once again, but this did not prevent the cyclone from resuming a west-northwest course. The period L6 wind profiles (Fig. 3.15d) are very similar to the L5 profiles, except the upper tropospheric westerlies at 6° continue to weaken and/or shift back to the east.

3.6 Summary of Left Turning Cyclones

During the first two periods (L3 and L4), the left turning cyclones moved on a north-northwest course. It is during these time periods that strong westerly winds occurred in the upper troposphere at 6 and 8° in octants 1 and 3. When these cyclones resumed a west-northwest course (periods L5 and L6) the strong westerlies which were in octant 1 at 6° weakened and shifted back to an easterly component between 250 and 350 mb. In addition, the westerlies which were in octant 3 during the first two time periods have shifted back to easterlies. It is likely that an upper level trough of tropical or mid latitude origin is responsible for the anomalous westerly winds to the north and west of the cyclone. These winds interact with the circulation of the cyclone in such a way to cause the cyclone to move on a northerly course. Once this feature by-passes to the north of the cyclone, easterly flow behind the trough resumes and the cyclone takes on a west-northwest course.

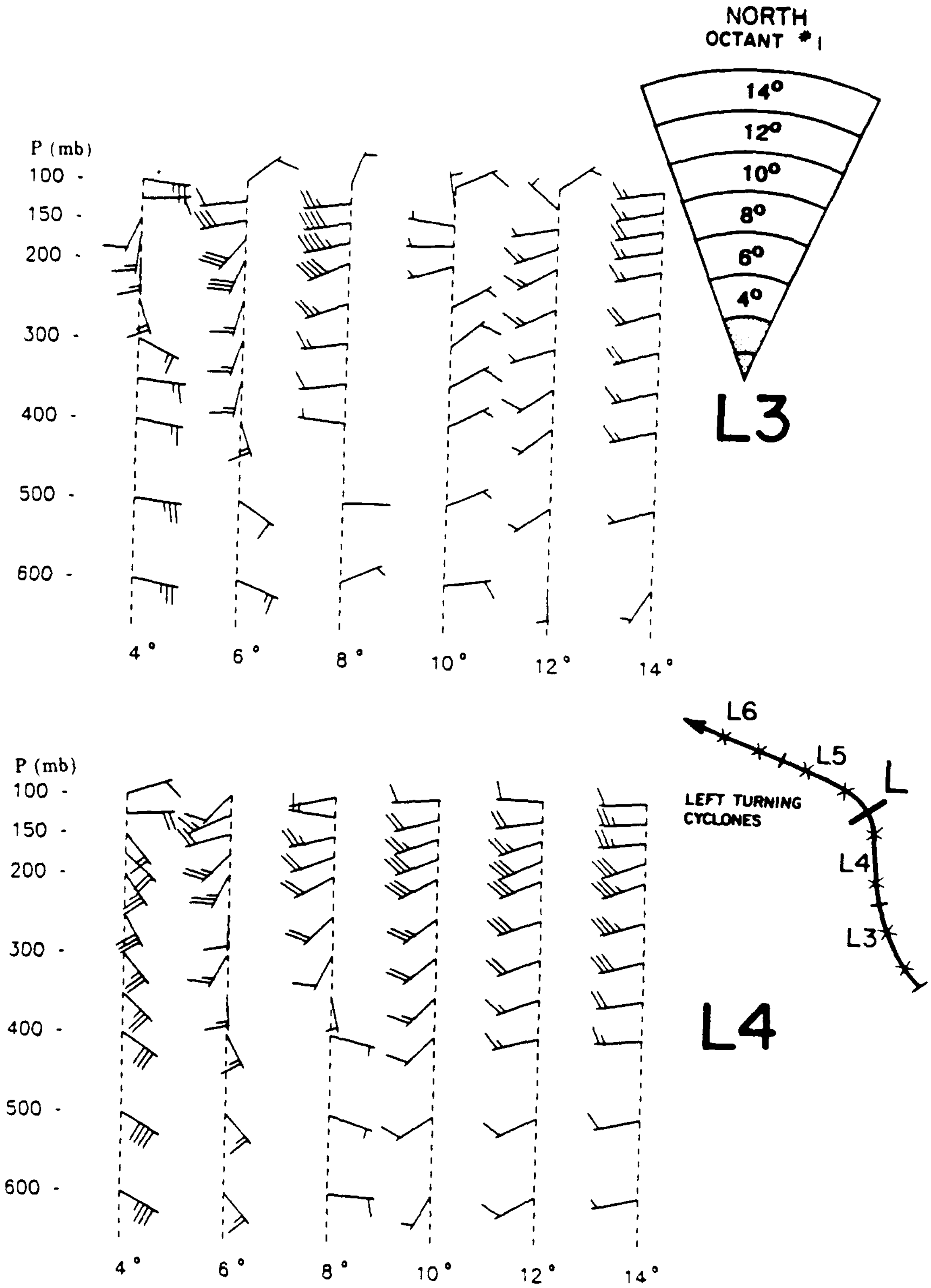


Figure 3.15: a-d. Vector wind profiles showing mid and upper tropospheric wind fields from 4 through 14 degrees in octant 1 for each of the 4 left turning time periods. Wind barbs plotted in standard meteorological format (knots).

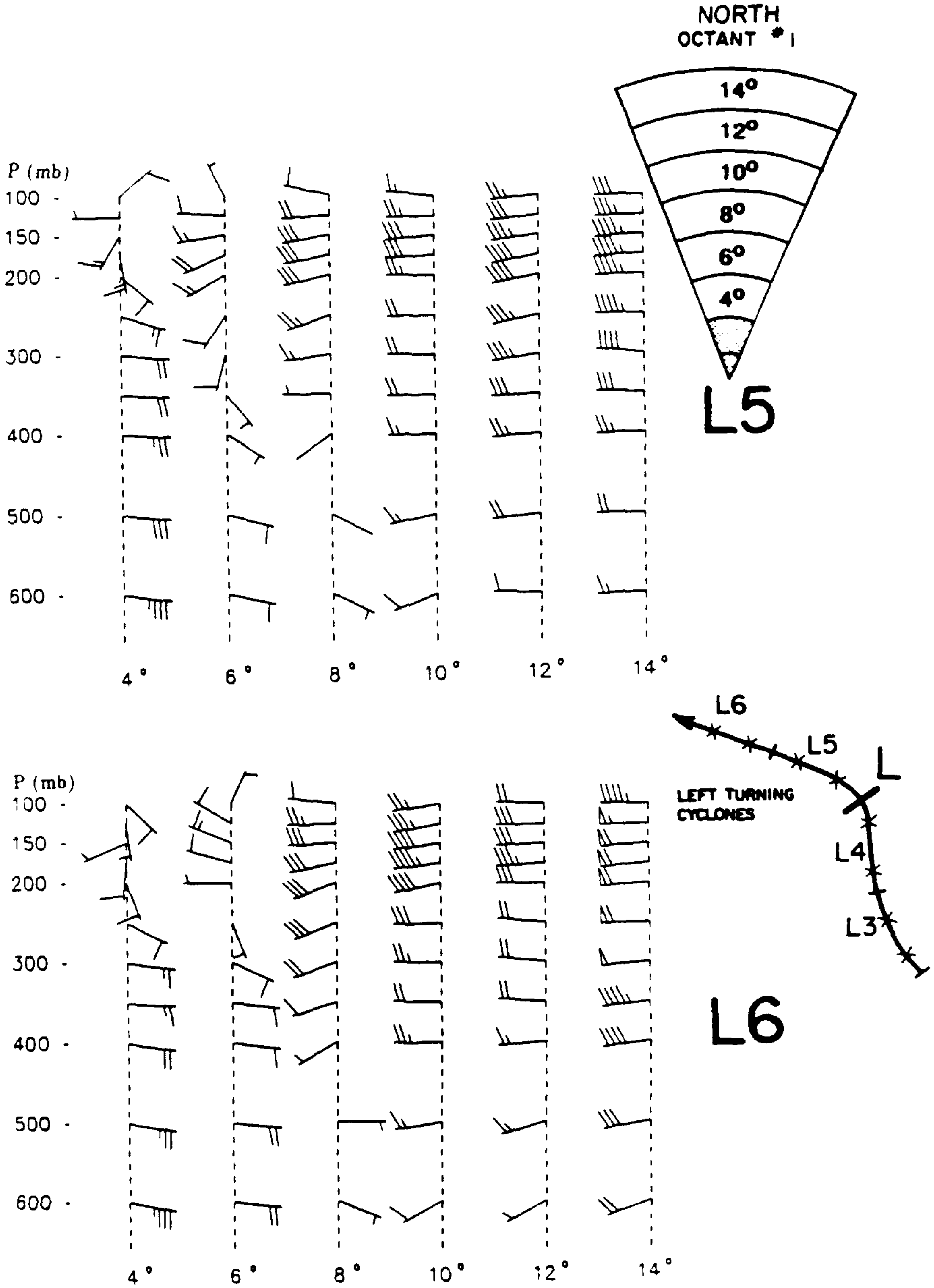


Figure 3.15: c-d. Continued.

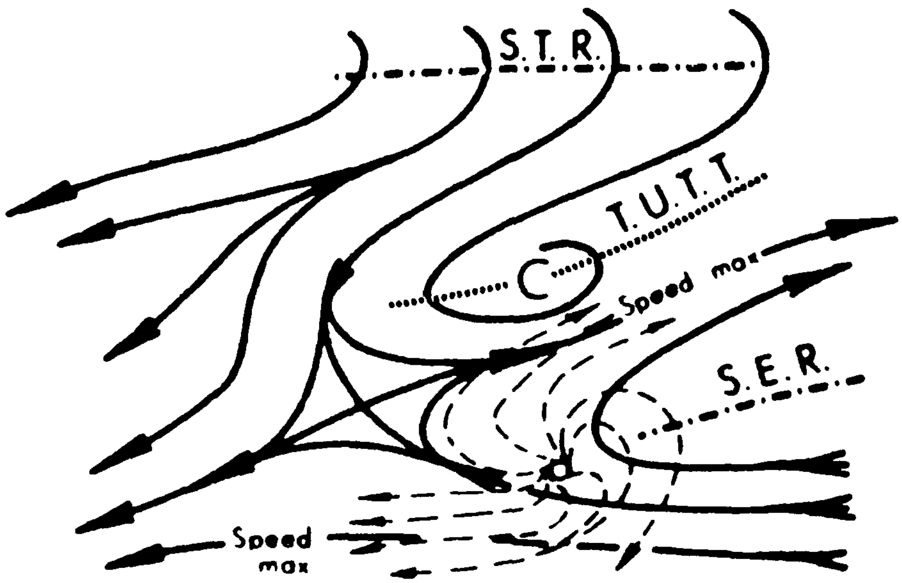


Figure 3.16: The upper tropospheric wind pattern associated with a TUTT cell. Note how the synoptic pattern north of the cyclone is similar to the upper tropospheric wind pattern shown in Fig. 3.13a. (From Sadler, 1976.)

3.7 Overall Summary of the Environmental Wind Fields of the Sharply Recurving, Slowly Recurving, Non-Recurving and Left Turning Cyclones

Environmental wind fields in the mid and upper troposphere at 6 and 8° radius north, northwest and west are critical for understanding future direction changes of tropical cyclones. The cyclones which recurved in this study did so only after positive zonal winds had penetrated the mid and upper troposphere at 6° radius to the northwest and west of the cyclone. Left turning cyclones also had anonymously strong wind fields at 6 and 8° radius north and west of center as the cyclones were moving in a north-northwesterly direction.

An interesting characteristic of nearly all cyclone stratifications which moved west during all or parts of their lifetimes (the non-recurving cyclones, westward moving cyclones, sharply and slowly recurving cyclones prior to beginning recurvature, and left turning cyclones after turning left) is that they had negative zonal (easterly) winds located in the 300-500 mb layer to the north, northwest and west at 6°, whereas tropical cyclones which were either recurving or moving north or northeast tended to have positive zonal wind located in the 300-500 mb layer in these same areas. Table 3.11 summarizes this result.

Table 3.11: Summary data for sign of zonal component in the 300- 500 mb layer for specific stratifications, time periods and octants.

Cyclone Time Periods		Was the Zonal Component of the Wind, 6 Degrees from the Cyclone's Center, Positive Anywhere in the 300-500 mb Layer in Octants 1, 2, or 3	Was the Cyclone Moving on a West Northwest Course (260-320 Degrees) at this Time
Non	NR1	NO	YES
Recurving	NR2	NO	YES
Cyclones	NR3	NO	YES
Sharply	R0	NO	YES
Recurving	R1	NO	YES
Cyclones	R2	NO	YES
	R3	YES	NO (RECURVING)
	R4	YES	NO (RECURVING)
Slowly	SR1	NO	YES
Recurving	SR2	NO	YES
Cyclones	SR3	YES	NO (RECURVING)
	SR4	YES	NO (RECURVING)
	SR5	YES	NO (RECURVING)
	SR6	YES	NO (RECURVING)
Left	L3	YES	NO (MOVING NNW)
Turning	L4	YES	NO (MOVING NNW)
Cyclones	L5	YES*	YES
	L6	NO	YES
Westward Moving Cyclones		NO	YES
Northward Moving Cyclones		YES	NO
Northeast Moving Cyclones		YES	NO

* At period L5, the zonal wind at the 300 mb level in octant 1 was positive but the speed was only 0.9 ms^{-1}.

Chapter 4

FORECASTING CYCLONE RECURVATURE USING 500 AND 200 MB WINDS

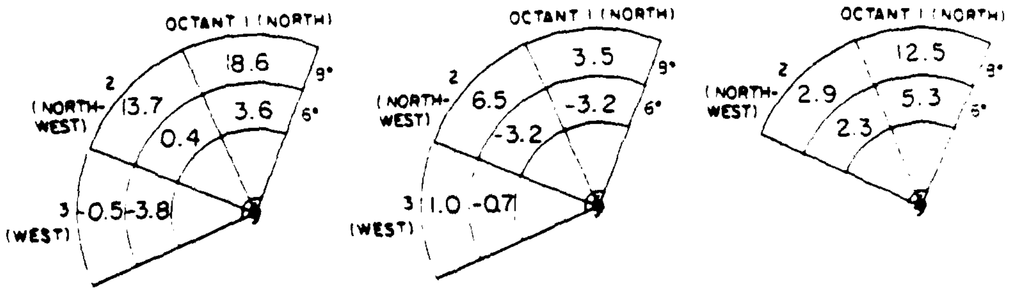
4.1 Introduction

This chapter proposes a recurvature forecast scheme which is based on the mid and upper tropospheric wind fields to the northwest of the cyclone. This forecasting scheme is relatively simple, and is designed to work using data available from computer analysis and prog wind fields. As was shown in the preceding chapter, when westerlies approached the northwest region of the cyclone, the cyclones began to recurve. Based on this result, it is proposed that by adding up the zonal components of the wind fields at the 500 and 200 mb, and the 200 mb meridional component of the wind [5] at the same locations, a numerical value of recurvature potential can be obtained. In general, this numerical value would remain negative as long as the cyclone is embedded in easterly flow at the 500 and 200 mb levels. As westerlies begin to develop to the northwest of the cyclone the value would tend to become less negative with time. As the westerlies increase in speed and penetrate closer to the cyclone this value becomes positive. The recurvature number should indicate the potential of possible change in cyclone direction in the near future. An example of the RECurvature NUMber, or RECNUM value is shown and an example calculation is made in Fig. 4.1.

[5]The 200 mb meridional wind fields are used in the forecast scheme to help differentiate sharply recurving cyclones from slowly recurving cyclones after they have begun to recurve. The environmental winds to the north and northwest of sharply recurving cyclones were strongly from the southwest while the winds to the north and northwest of slowly recurving cyclones were from a more west-southwesterly direction and were weaker in magnitude.

Recurvature Number Equation

$$\sum_{i=\mathrm{Oct}\,1}^{3} \frac{(u_{8^\circ}+u_{6^\circ})}{2}\,200\mathrm{mb} + \sum_{i=\mathrm{Oct}\,1}^{3} \frac{(u_{8^\circ}+u_{6^\circ})}{2}\,500\mathrm{mb} + \sum_{i=\mathrm{Oct}\,1}^{2} \frac{(V_{8^\circ}+V_{6^\circ})}{2}\,200\mathrm{mb}$$



200mb u 500mb u 200mb v

RECNUM value calculated for the sharply recurving time period of R2:
[(18.6 + 3.6) + (13.7 + 0.4) + ((-0.5) + (-3.8))
+ (3.5 + (-3.2)) + (6.5 + (-3.2)) + (1.0 + (-0.7))
+ (12.5 + 5.3) + (2.9 + 2.3) 1/2 = ~ 30

Figure 4.1: The equation used to calculate the recurvature number (RECNUM) values. An example of how the RECNUM value is calculated is shown using wind fields from the sharply recurving data set at period R2.

Figure 4.2 shows mean RECNUM values for the sharply recurving, slow recurving, left turning and non-recurving time periods in this study. Cyclones moving on a westerly course typically had negative RECNUM values; when the cyclones were moving north or northeast, RECNUM values were positive. Recurvature numbers of sharply recurving cyclones increased rapidly during the time when the cyclones were recurving while the values increased only gradually during the time when the slowly recurving cyclones were recurving. Non-recurving cyclones had varying negative RECNUM values during all three time periods.

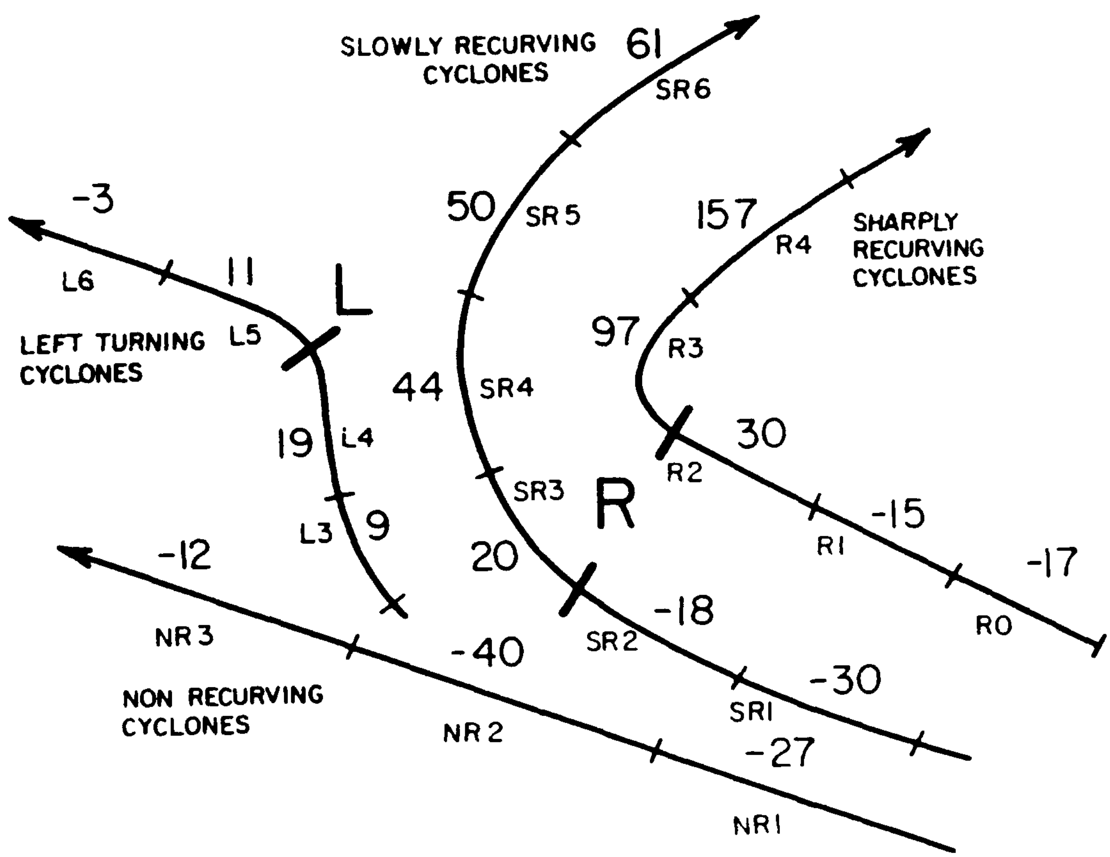


Figure 4.2: RECNUM values for the sharply recurving, slowly recurving, left turning and non-recurving cyclone time periods.

Exceptions to the negative RECNUM values for west-northwest motion occurred for two time periods; sharply recurving time period R2, and at left turning period L5. At period R2, a RECNUM value of +30 was computed whereas prior to R2, the RECNUM values were negative. This sharp change indicates that environmental winds north and west of the cyclone have taken on positive (zonal and meridional) components, thereby indicating that a possible change in the direction of the cyclone might occur. The RECNUM value for the left turning cyclones at period L5 was also positive (+11), but prior to this time period, when the cyclones were moving north (period L4), the RECNUM value was larger. It can be seen as the left turning cyclones went from a northerly to a westerly direction, the RECNUM values decreased with time.

4.2 Data

To test if recurvature numbers have value for predicting recurvature, RECNUM values were calculated for 55 tropical cyclones which developed during the 1984, 1985 and during the first 6 months of the 1986 Northwest Pacific tropical cyclone seasons. Environmental wind field data needed for calculating recurvature numbers was acquired from objective analysis fields generated by the Australian Bureau of Meteorology Research Center (BMRC). The BMRC objective analyses included zonal (u) and meridional (v) winds at various levels in the troposphere. The wind field data were available on a 2.5° latitude–longitude grid extending from 40° N to 20°S and 100° through 180° E. Figure 4.3 shows examples of the 500 and 200 mb BMRC wind field analyses.

Since each recurvature number was calculated relative to the cyclone center, the position of the cyclone at each 12 hour time period had to be found relative to the 500 and 200 mb BMRC analysis fields. Once this was accomplished, a linear interpolation technique was employed on the BMRC objective analysis to find the zonal and meridional components of the wind fields in areas 6 and 8° to the north, northwest and west of the cyclone.

4.3 Results

Results for this test showed that the recurvature numbers relate fairly well to tropical cyclone direction. As can be seen in Fig. 4.4, 42% of the variance in cyclone direction was

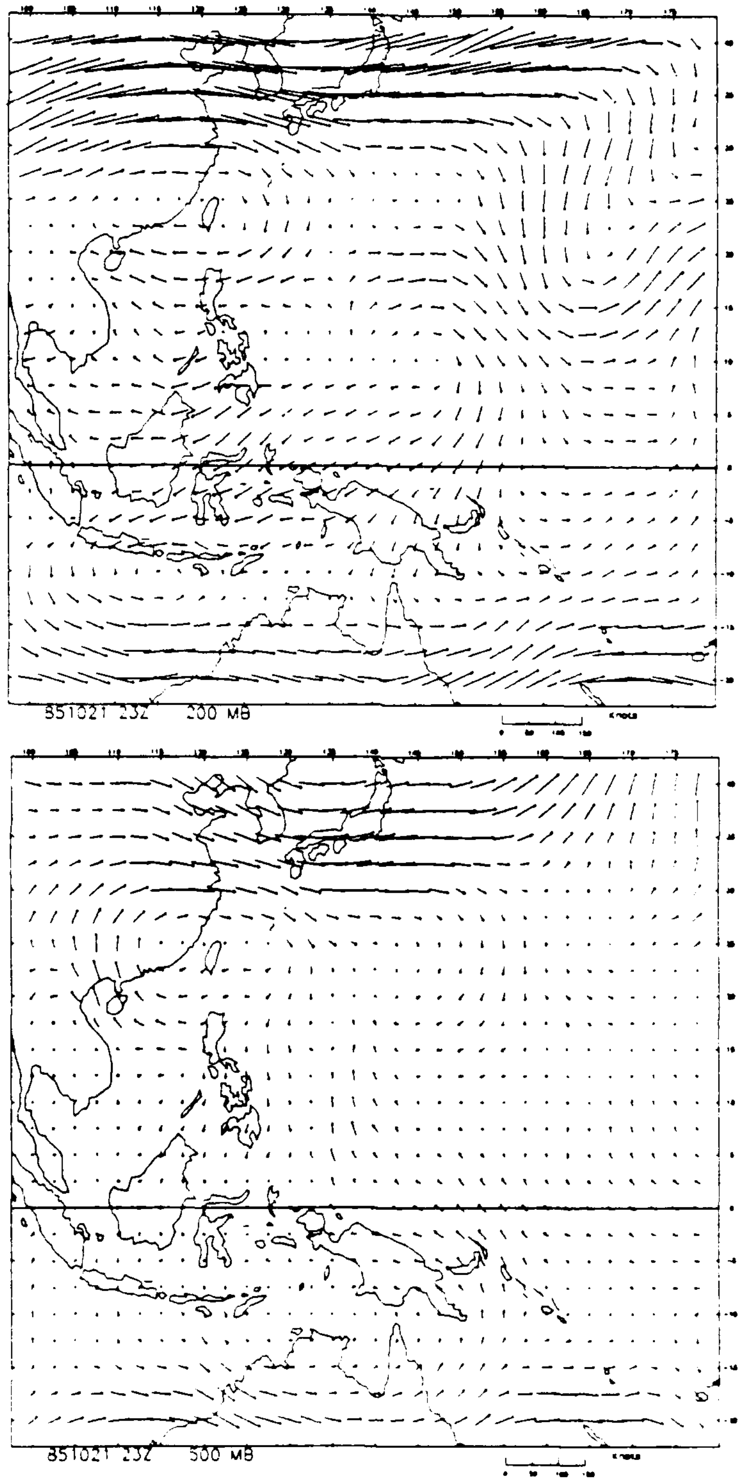


Figure 4.3: An example of the 200 and 500 mb BMRC objective analysis winc. fields.

explained by the 500 and 200 mb wind field data to the north, northwest, and west of the cyclone. Some of the scatter in Fig. 4.4 is likely caused by strong vertical wind shear and by data deficiencies in the BMRC analysis. Vertical wind shear is a problem for the following reason: When a cyclone moves into a highly sheared environment, convection near the center is displaced upstream away from the center of the storm. When this occurs, the exposed low level circulation will be steered by the low level wind flow currents which, for a majority of the time, are from an easterly direction (which will steer the low-level center towards the west) while the winds which sheared off the convection are typically from a westerly direction. The strong westerlies aloft correspond to a large positive recurvature number which represents northeast motion although the low level storm center will be moving to the west (Fig. 4.5). Another synoptic situation which causes scatter in the data occurs when two cyclones approach one another and the cyclones undergo what is termed a binary interaction (Fig. 4.6).

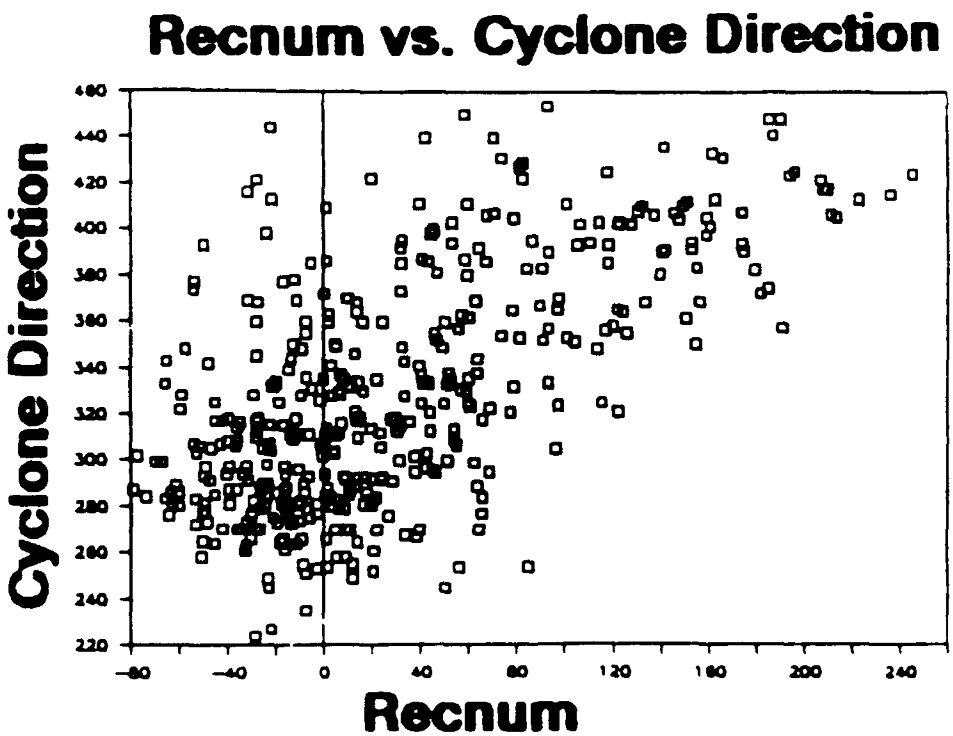


Figure 4.4: Scatter diagrams showing how the RECNUM value relates to tropical cyclone direction (Note: The direction values plotted on the ordinate which are greater than 360 represent motion east of due north; example "400" = 400-360 or 040 degrees).

DATE	RECNUM VALUE	RECNUM DIRECTION	ACTUAL DIRECTION	DIRECTION DIFFERENCE (RECNUM minus ACTUAL)
4/28/12Z	52	341	338	3
4/29/00Z	42	336	297	39
4/29/12Z	40	335	270	65
4/30/00Z	64	347	270	77
4/30/12Z	56	343	254	84
4/01/00Z	n/a	—	243	—
4/01/12Z	n/a	—	292	—
4/02/00Z	57	344	307	37
4/02/12Z	67	348	297	51
4/03/00Z	46	338	295	43

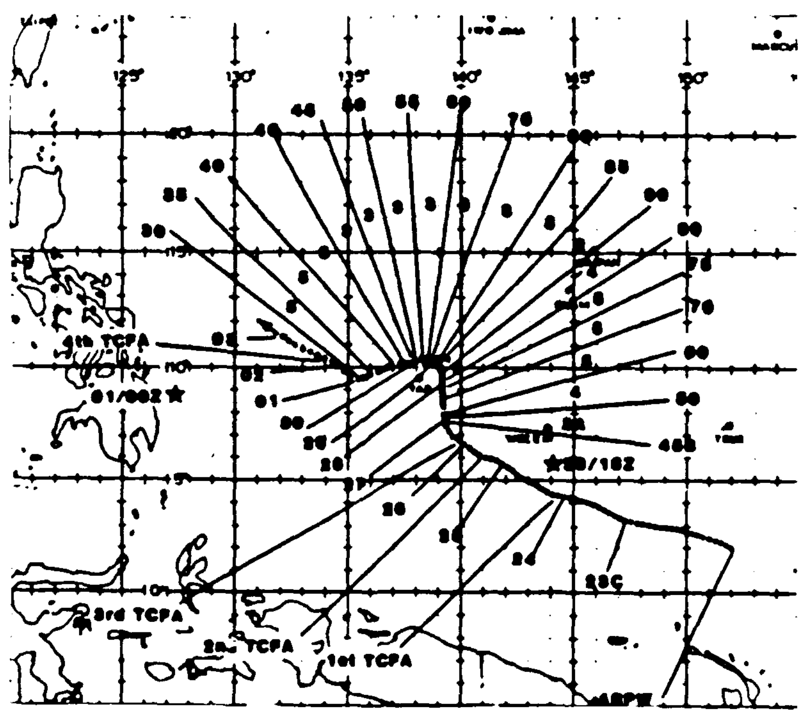


Figure 4.5: RECNUM values calculated for Typhoon Ken (1986) as Ken was moving west. During this time strong westerlies had sheared the convection off towards the northeast exposing a low level circulation center which was consequently steered by the low level trade wind flow. The strong westerly winds aloft relate to large RECNUM values which are representative of northward motion (JTWC 1986).

		Tropical Cyclone Odessa		
DATE	RECNUM VALUE	RECNUM DIRECTION	ACTUAL DIRECTION	DIRECTION DIFFERENCE (RECNUM minus ACTUAL)
8/29/00Z	-10	311	292	19
8/29/12Z	14	323	291	32
8/30/00Z	28	330	277	53
8/30/12Z	65	348	254	94
8/31/00Z	84	357	045	47
8/31/12Z	79	354	048	54

		Tropical Cyclone Pat		
DATE	RECNUM VALUE	RECNUM DIRECTION	ACTUAL DIRECTION	DIRECTION DIFFERENCE (RECNUM minus ACTUAL)
8/29/00Z	-28	302	061	-119
8/29/12Z	-24	304	038	-94
8/30/00Z	-10	311	010	-59
8/30/12Z	46	338	355	-17
8/31/00Z	91	360	352	8
8/31/12Z	179	043	022	21

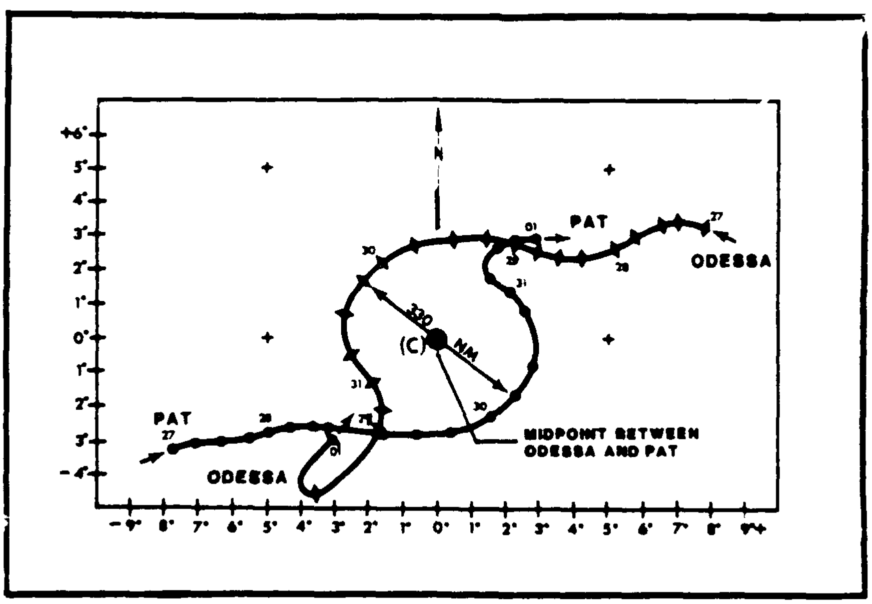


Figure 4.6: During the dates of 8/29/00z and 8/31/12 1985, tropical cyclones Pat and Odessa underwent a complicated binary interaction. This interaction related to a poor relationship between the RECNUM values and actual cyclone direction (JTWC 1985).

In addition to vertical wind shear and binary interactive process, data deficiencies in the BMRC analysis could also contribute to the scatter in Fig. 4.4. It is well known that data availability in the tropics, especially in the mid troposphere, is poor. Although the flow fields in the BMRC analysis scheme are likely to be the best available, if the data which went into the analysis was inaccurate, then the RECNUM values themselves must also be inaccurate.

4.4 Real-Time Test of the RECNUM Forecasting Scheme During TCM-90

To see if the recurvature numbers could predict tropical cyclone direction on a real time basis, the RECNUM forecasting scheme was employed during the Tropical Cyclone Motion experiment (TCM-90) which was conducted on the island of Guam during the summer of 1990 (Elsberry, 1990). During this experiment, recurvature numbers were calculated using data from the U.S. Navy NOGAPS analysis/prognostic wind fields. Since the analysis and prognostic wind fields were identical in format to the BMRC objective analysis, no major modifications of the RECNUM forecasting scheme were necessary. Recurvature numbers were calculated with respect to every gridpoint on the analysis and the 24, 48 and 72 hour prognostic fields instead of the cyclone's current position. This procedure was necessary simply because future cyclone positions were unknown. Figure 4.7 shows an example of recurvature number grids and also lists the direction of motion to which these numbers relate, based on the equation:

$$Cyclone\ Direction\ = 315.09 + 0.4839\,(RECNUM\ Value)$$

which was derived from Fig. 4.4. During the experiment, tropical cyclone motions were forecasted using the recurvature numbers in the following way: The position (latitude/longitude) of the cyclone at t = 0 was found on the RECNUM direction analysis grid. The cyclone was then advected, based on this RECNUM direction, for the first 24 hours (The speed of the cyclone was usually based on persistence and/or climatology). The location of the cyclone at the end of the first 24 hour time period was then located on the 24 h RECNUM/direction grid, a new direction was found, and the cyclone was advected in this new direction for the next 24 hours. This same procedure was repeated to find the location of the cyclone at 48 and 72 hours after the initial forecast time.

RECNUM GRID FOR: 90072512

LONGITUDE

100 +	10.0	12.5	15.0	17.5	20.0	22.5	25.0	27.5	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	50.0	52.5	55.0	57.5	60.0
35.0	115	105	98	98	102	103	97	86	74	61	51	40	28	17	6	-9	-26	-36	-31	-10	15
32.5	83	73	67	67	66	59	49	37	26	16	7	-4	-15	-25	-36	-47	-51	-42	-22	4	22
30.0	44	39	36	31	22	10	0	-6	-11	-19	-29	-40	-50	-61	-67	-63	-45	-19	4	20	25
27.5	10	8	3	-9	-22	-30	-32	-32	-34	-40	-50	-59	-67	-72	-65	-45	-17	7	22	27	22
25.0	-13	-18	-28	-42	-51	-52	-47	-44	-46	-52	-59	-66	-67	-56	-36	-11	8	19	24	23	18
22.5	-25	-34	-47	-55	-56	-52	-47	-48	-53	-57	-60	-60	-53	-32	-8	7	13	14	13	11	7
20.0	-33	-42	-51	-51	-46	-41	-41	-44	-48	-49	-47	-41	-29	-12	3	7	4	1	-2	-3	-4
17.5	-38	-44	-46	-41	-36	-35	-35	-34	-31	-28	-22	-14	-6	0	4	-0	-8	-14	-18	-18	-15
15.0	-39	-40	-38	-34	-32	-32	-29	-22	-13	-7	-3	2	5	4	-0	-11	-23	-33	-36	-32	-25
12.5	-34	-32	-29	-26	-23	-20	-15	-8	-2	-0	1	2	3	-1	-10	-26	-42	-50	-48	-39	-30
10.0	-30	-27	-23	-19	-12	-6	-2	-2	-4	-7	-9	-8	-8	-15	-27	-45	-58	-59	-50	-39	-30
7.5	-32	-30	-26	-21	-15	-11	-12	-18	-24	-28	-29	-29	-32	-41	-52	-63	-66	-58	-45	-36	-30
5.0	-41	-41	-39	-36	-35	-38	-43	-50	-55	-56	-56	-58	-62	-69	-75	-74	-66	-53	-41	-35	-32

RECNUM DIRECTIONS FOR: 90072512

LONGITUDE

LATITUDE

100 +	10.0	12.5	15.0	17.5	20.0	22.5	25.0	27.5	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	50.0	52.5	55.0	57.5	60.0
35.0	373	368	363	363	366	366	363	357	350	343	337	331	325	319	313	305	295	290	292	304	318
32.5	355	350	347	346	346	342	336	330	324	319	313	308	302	296	290	284	282	287	298	312	322
30.0	334	331	329	327	322	315	310	306	303	299	294	288	282	276	273	275	285	299	312	321	323
27.5	315	314	311	305	297	293	292	292	291	287	282	277	273	270	274	285	300	313	322	324	322
25.0	302	300	294	287	281	281	284	285	284	281	277	273	273	279	290	303	314	320	323	322	318
22.5	296	291	284	279	279	281	283	283	280	278	277	276	281	292	305	314	317	317	317	316	313
20.0	292	286	282	282	284	287	287	285	283	282	284	287	293	303	311	313	312	310	309	308	308
17.5	289	286	284	287	290	290	290	291	292	294	297	302	306	310	312	309	305	302	300	300	301
15.0	288	287	289	291	292	292	293	298	303	306	308	311	312	312	309	304	297	292	290	292	296
12.5	291	292	294	295	297	298	301	305	308	309	310	311	311	309	304	295	286	282	283	288	293
10.0	293	295	297	299	303	306	308	308	307	306	305	305	305	302	294	285	278	277	282	288	293
7.5	292	293	295	298	301	303	303	300	296	294	294	294	292	287	281	275	273	278	285	290	293
5.0	287	287	288	290	290	289	286	282	279	279	279	278	275	271	268	269	273	280	287	291	292

Figure 4.7: An example of the RECNUM grid values (top) and RECNUM directions (bottom).

Figure 4.8 shows two cyclones for which the recurvature numbers were used to forecast motion[6]. The first cyclone, Yancy, moved on a west-northwest course throughout most of its lifetime, except when it was east of Taiwan. During this time, a mid latitude trough was moving to a position north of the cyclone. At this time it was uncertain whether the cyclone would recurve or would resume motion to the west-northwest. The

[6]Unfortunately, only 2 cyclones were forecasted using the RECNUM forecasting scheme. This was due to computer ingest problems which developed at JTWC during the second part of the experiment (Sept. 1 - Sept. 23). With the ingest system down, JTWC could not receive the NOGAPs data which was needed to run the forecast scheme.

RECNUM forecast made at 08/18/0000z (Fig. 4.9) forecasted the cyclone to take on a west-northwest course during all three 24 forecast time periods. Although the cyclone did turn towards the north-northwest during the first 24 hour time period, the cyclone did resume a west-northwest course during the second and third forecast periods.

The second tropical cyclone, Zola, had two track deviations in its lifetime that were quite significant. The first occurred 18/1800z when the cyclone turned sharply back towards the northwest from a previous northeast course. The RECNUM forecast made 18 hours earlier (18/0000z, Fig. 4.10a) forecast this track change. The second track deviation occurred when the cyclone actually underwent recurvature on 22/0000z over Southern Japan. The RECNUM forecast made 19/0000z (Fig. 4.10b) predicted the cyclone to move on a northwest course during the first 48 hours, but then forecasted the cyclone to begin gradually turning the to the right at 72 hours (22/0000z). The RECNUM forecast made on the 20/0000z (Fig. 4.10c) again showed the cyclone moving northwest during the next 48 hours, but by 72 hours (23/0000z), the cyclone would have undergone recurvature. As can be seen in Fig. 4.10c, the cyclone actually underwent recurvature at 22/0000z. A problem which the RECNUM forecast scheme had with Zola was speed. This is to be expected since the speed of the cyclone was based on a mix of persistence and climatology. It is likely if the author had increased Zola's speed with time prior to recurvature, the forecast would have been very close to the actual track verification.

4.5 Summary

The recurvature number forecast for both storms was quite promising. The RECNUM forecast for Yancy to move west-northwest (made while it was still east of Taiwan) was beneficial, even though the cyclone moved on a north-northwest course during the first 24 hour forecast time period. Hopefully, the RECNUM forecast would benefit the forecaster in this case by making him/her aware that the environment to the northwest of the cyclone was not favorable for recurvature, and that any change of course was likely to be only for a short time.

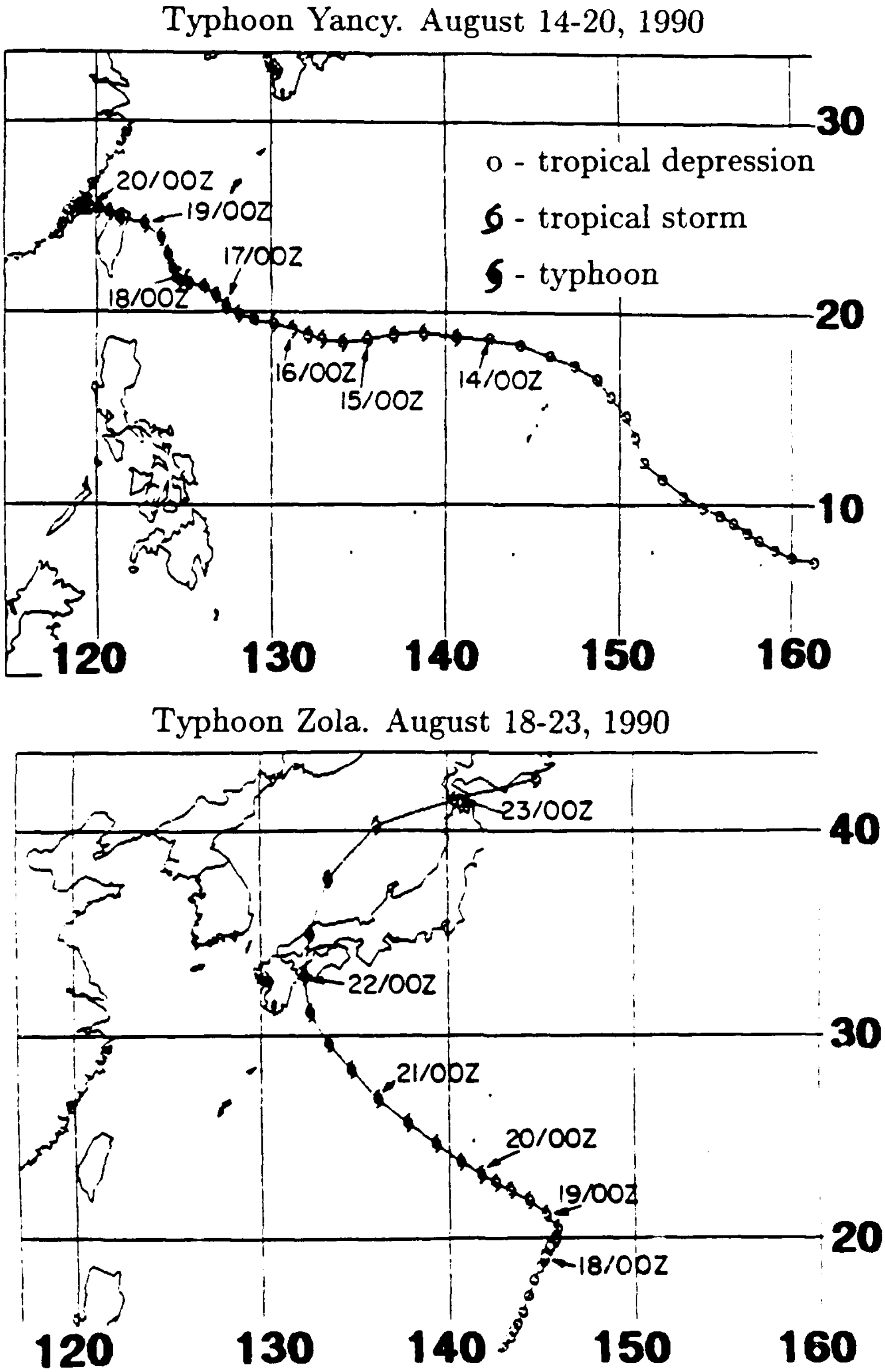


Figure 4.8: Working best tracks of Typhoon Yancy (top) and Zola (bottom).

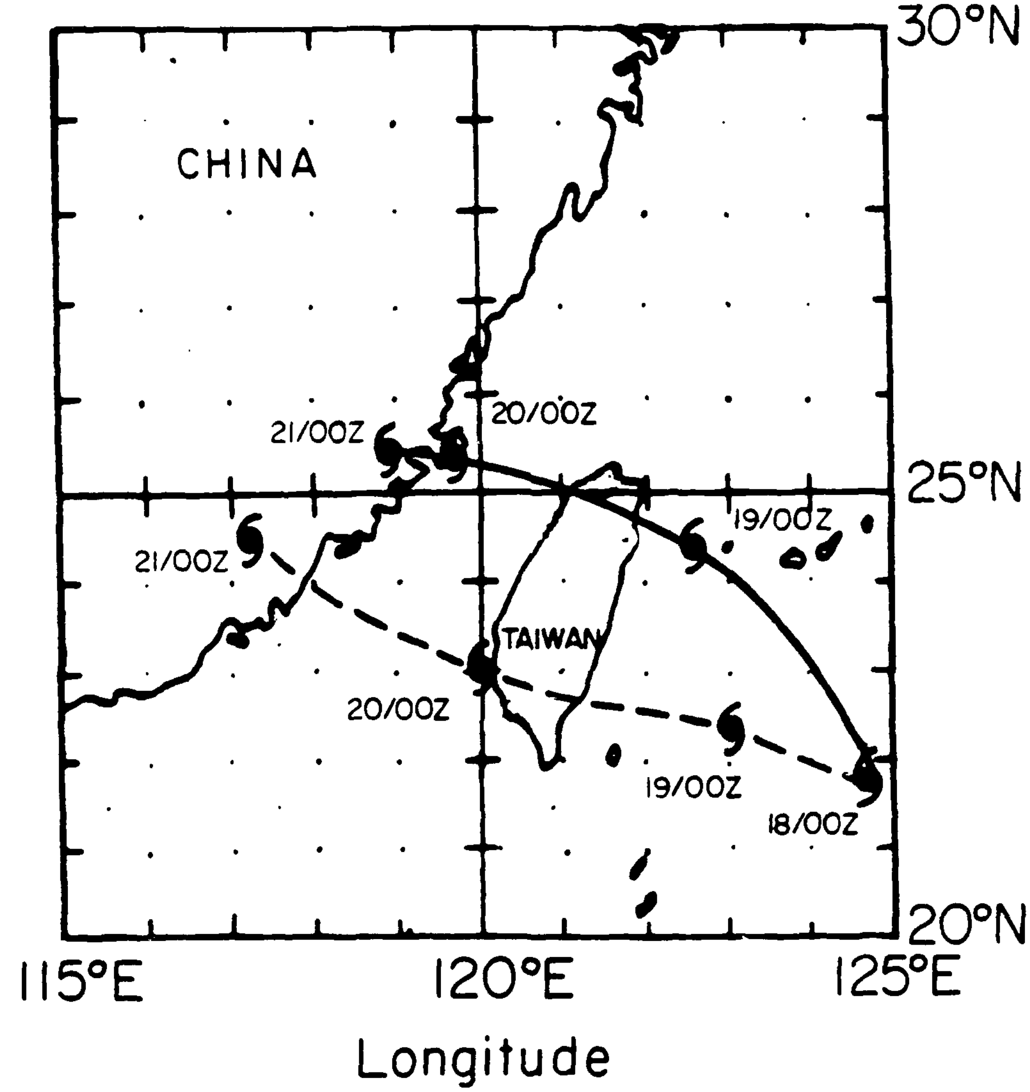


Figure 4.9: RECNUM forecast made 18 Aug. 0000z (dashed line) and actual working best track (solid line) of Typhoon Yancy.

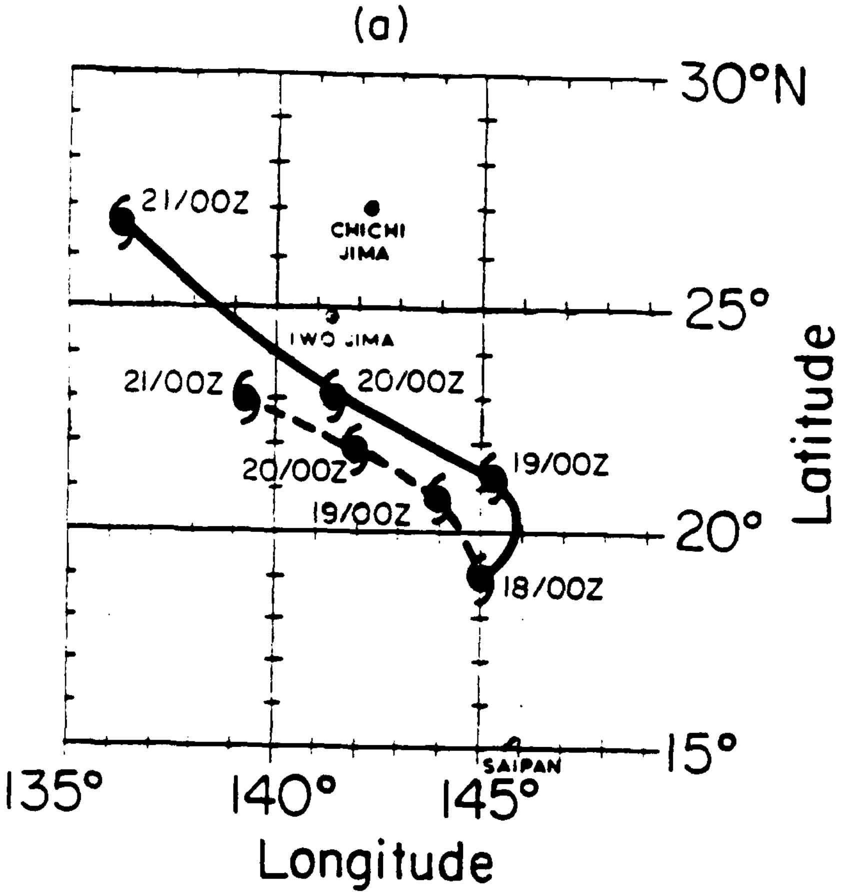


Figure 4.10: a-c: RECNUM forecast made 18 Aug. 0000z (A), 19 Aug. 0000z (B) and 20 Aug. 0000z (C). Dashed line represents RECNUM forecast while solid line represents actual working best track of Typhoon Zola.

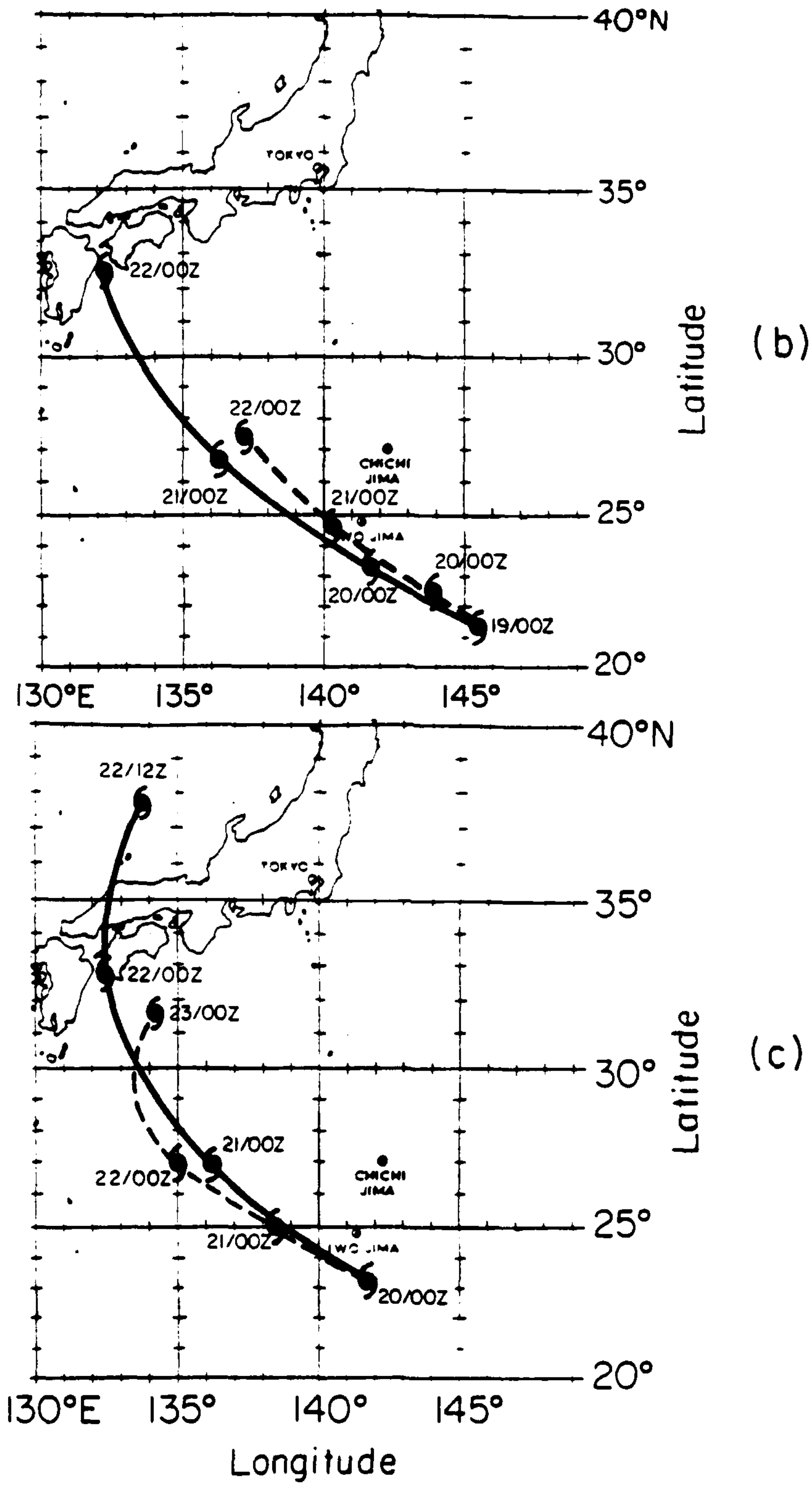


Figure 4.10: b-c: Continued.

The RECNUM forecast predicting Zola's two track deviations was also very favorable. The forecast for the first track deviation showed that, as the recurvature numbers to the poleward side of the cyclone decreased with time, the cyclone would turn to the left and resume a west-northwest course. The second track deviation was also predicted correctly, albeit the RECNUM speed forecast was slow. The RECNUM forecast did show that as the recurvature numbers to the north of the cyclone increased with time, the likelihood of the cyclone recurving to the northeast also increased.

Chapter 5

SUMMARY DISCUSSION

Previous research related to tropical cyclone recurvature showed that the environmental wind fields to the poleward side of the cyclone were important for indicating if the tropical cyclone was going to remain on a west-northwest course or recurve. As was shown by George and Gray (1976), 200 mb westerly winds 8 to 20° north and west of the pre-recurving cyclones increased in speed with time as the cyclone approached the point of beginning recurvature. However, when Guard (1977) used the results of George and Gray's (1976b) study to predict recurvature on a real time basis, he found that their scheme over-predicted recurvature about 25% of the time. The primary reason why these cyclones in Guard's study did not recurve even though the 200 mb wind fields were favorable for recurvature was that the westerlies did not penetrate close enough nor deep enough to the cyclone center. As was shown in Chapter 3, westerlies in the upper troposphere could reach to within 8° of the cyclone's center, and not have any effect on changing the cyclone's direction of motion. It wasn't until the westerlies reached below the 300 mb level and to within 6° from the center that beginning rightward turning and recurvature commensed.

This study emphasizes the importance of mid-to-upper tropospheric zonal wind fields as primary distinguishing factors between recurvature and non-nonrecurvature. Rather than use the wind fields at or below the 500 mb level, forecasters should instead attempt to utilize wind fields in the mid and upper troposphere (200, 300 and 400 mb) as the best indications of future cyclone recurvature potential.

Recurvature forecast schemes should be based on the analysis of environmental wind fields on the north through west sides of the tropical cyclone. The recurvature forecasting scheme which was presented in this paper showed promising results. We recommend this simple and empirical method for predicting tropical cyclone recurvature, and hope that this forecast scheme may be of some assistance at cyclone forecasting centers. Note that this recurvature forecast scheme is based on historical information on how the atmosphere has behaved in the past and has no built-in analysis biases which can creep into computed analysis schemes, particularly in data void regions. In this study no analyses were made if data was not present.

Based on the results of this study, recurvature forecasting is dependent on how accurately the mid-to upper tropospheric wind fields at 6 and 8° to the north through west of the cyclone can be measured. Other more complicated information on the tropical cyclone, such as wind fields on the equatorward side or eastward side of the cyclone, cyclone structure, extent of deep convection and convective asymmetry are not required. These many other pieces of information which most PE numerical models attempt to incorporate, can add unneeded complication and confusion to the recurvature forecast and may obscure the recurvature decision which the forecaster is required to make.

The next step is to verify the extent to which this recurvature composite information can be utilized on an individual case basis. The enhanced rawinsonde data network provided by the recent Northwest Pacific Tropical Cyclone Motion experiment (TCM-90) will be extensively analyzed to determine the extent to which this rawinsonde composite information can be utilized in individual case recurvature forecasts. If it is found that the mid- to upper troposheric wind fields are important for predicting individual case tropical cyclone motion change, then consideration might be given to aircraft reconnaissance (such as that available with a Gulfstream type aircraft) to fly at upper tropospheric levels 6 – 8° to the northwest side of the cyclone to help improve the operational recurvature forecast.

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Appendix A

WIND VECTOR PROFILES OF THE SHARPLY RECURVING, SLOWLY RECURVING, NON-RECURVING AND LEFT TURNING CYCLONES

As was discussed earlier in Chapter 2, wind field data throughout the troposphere were initially analyzed from 4 to 14° from the center of the cyclone. The wind field data at 6 and 8° were chosen to study pre-recurvature because it was shown that once positive zonal winds reached to within 6° of the cyclone, the cyclone began to recurve. The zonal winds at 8° were considered important because once progressively increasing positive zonal winds reached this radius the cyclone will likely begin to recurve in the next 24 hours. In this section, wind vector profiles are employed to show that the wind fields at 8° and beyond play no direct role in actually causing the cyclone to change its direction.

A.1 Wind Vector Profiles of Non-recurving Cyclones

Figure A.1 through A.3 show the wind vector profiles in octants 1, 2 and 3 for the three non-recurving cyclone time periods. As can be seen, the first non-recurving time period, NR1 (Fig. A.1), shows the wind fields in all three octants are primarily from an easterly component, except in octant 1 where weak westerlies [7] exist throughout a majority of the troposphere at 12 and 14°, and at the 200-300 mb level at 4 through 10°. At period NR2 (Fig. A.2), the westerlies in octant 1 have increased in speed and have moved to within 10° of the cyclones' center. The vector wind profiles at period NR3 (Fig. A.3), show that the westerlies have now reached to within 8° of the cyclones in octant 1,

[7] Unless otherwise specified, "westerlies" refer to any wind direction between 200 and 330 degrees.

and to within 10° in octant 2, but the cyclones still continued to move west-northwest. It is very important to notice that, in octant 1, mid and upper tropospheric westerly winds could exceed 10 to 20 ms^{-1} (20 to 40 knots) [8] as close in as 10°, and not have any affect on the motion of the cyclone.

A.2 Wind Vector Profiles of the Slowly Recurving Cyclones

Figure A.4 through A.9 show the wind vector profiles in octants 1, 2 and 3 for the six slowly recurving cyclone time periods. At period SR1 (Fig. A.4), the tropical cyclones are embedded in easterly flow from 4 through 10° in all three octants. Westerlies exist at 12 and 14° in octants 1 and 2, and weak westerlies also exist in the lower troposphere in octant 3. At period SR2 (Fig. A.5), westerly winds have reached to within 8° of the cyclone in octant 2, and to within 10° in octant 1. Weak westerly winds in the mid and lower troposphere are also apparent in octant 3. It is important to note that these cyclones are only ~12 hours away from beginning slow recurvature, but the westerly winds 10° from the cyclone in octant 1 are only 5 ms^{-1}, while the westerlies at the same radius in octant 2 average 7 ms^{-1}. As the slowly recurving cyclones begin to recurve during period SR3, the vector wind profiles at this time period show that weak south-south westerly winds in the mid and upper troposphere have reached to within 6° of the cyclones' center in octant 2, and the winds in octant 3 have switched from an easterly to a westerly component in the mid and lower troposphere. Surprisingly, the westerly winds at distances beyond 8° in octants 1 and 2 are relatively weak, ranging in speeds of 7 to 12 ms^{-1} at 8 and 10°, to 10 to 15 ms^{-1} at 12 and 14°. During the remaining three slowly recurving time periods, SR4, SR5 and SR6 (Fig. A.7 through A.9) the westerly winds to the north and northwest and west of the cyclone gradually pick up speed.

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[8]The wind vectors in the figures are plotted in knots. The wind speeds in the text are ms^{-1}.

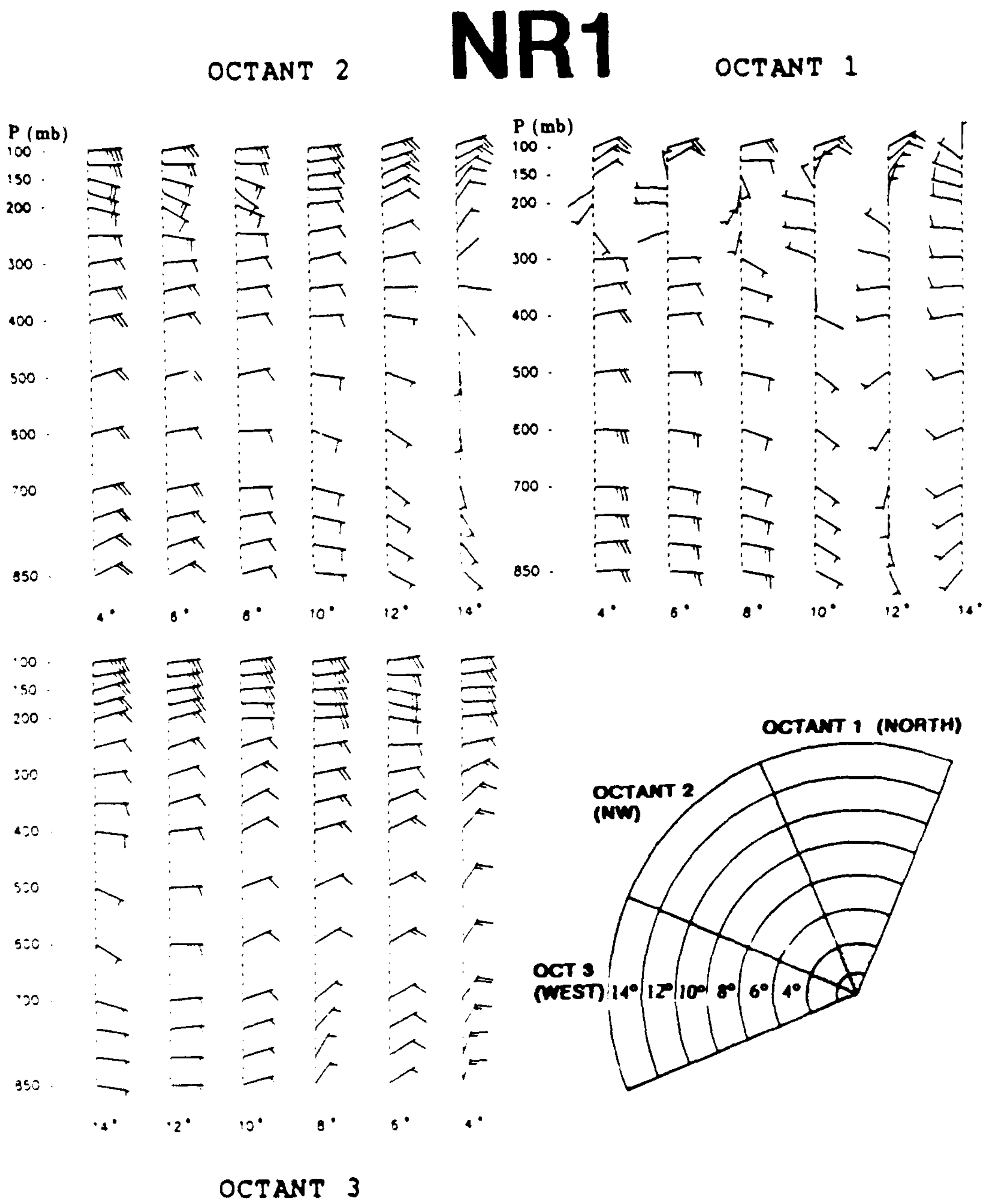

Figure A.1: Wind vector versus radius profiles in octant 1 (top), 2 (upper left) and 3 (left) of the non-recurving cyclones at period NR1. Note the change in radii for octant 3. Wind barbs plotted in standard meteorological format (knots). See Figure 2.11 for definition of cyclone time periods.

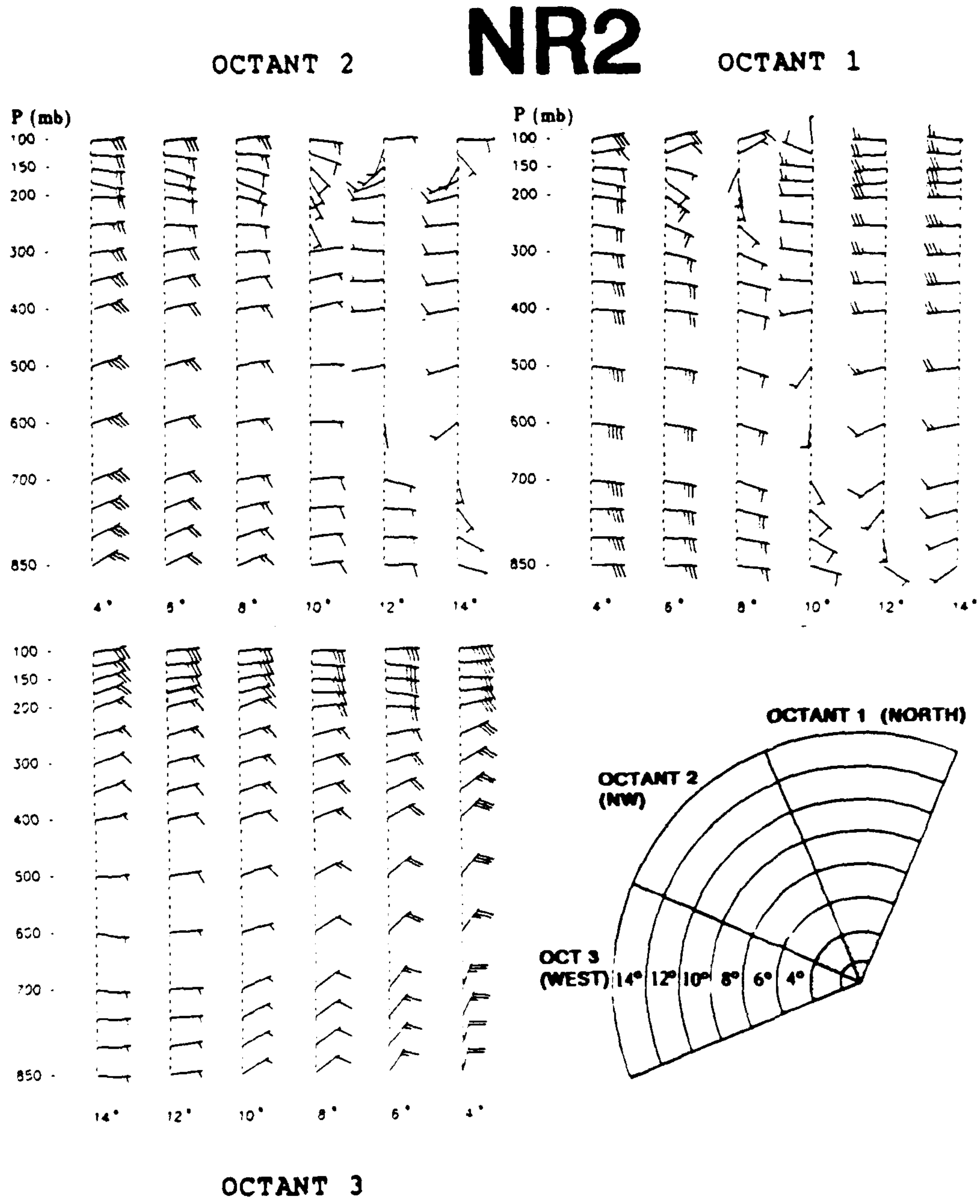

Figure A.2: Same as Fig. A.1 except for non-recurving cyclones at period NR2.

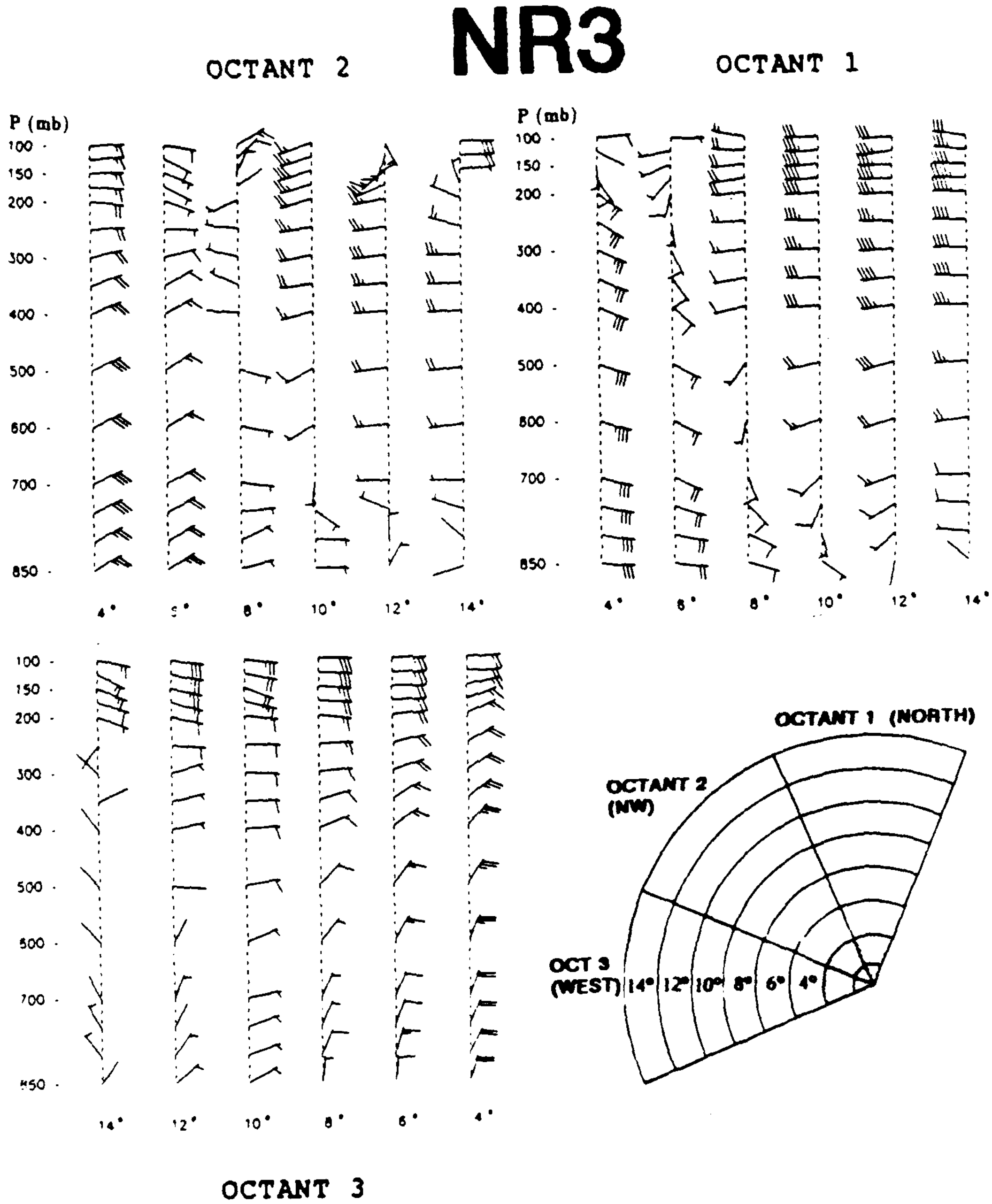

Figure A.3: Same as Fig. A.1 except for non-recurving cyclones at period NR3.

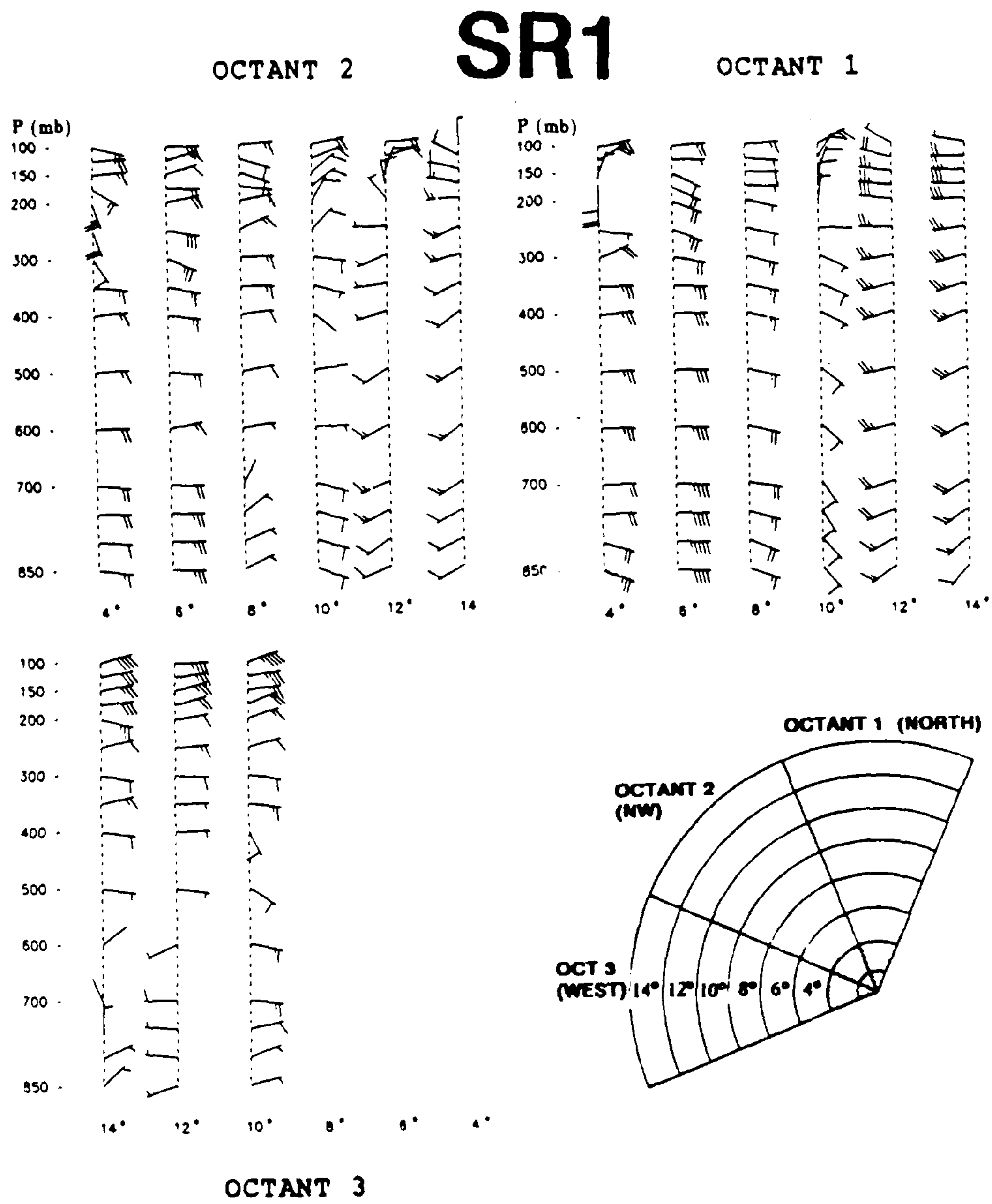

Figure A.4: Wind vector versus radius profiles in octant 1 (top), 2 (upper left) and 3 (left) of the slowly recurving cyclones at period SR1. See Figure 2.11 for definition of cyclone time periods.

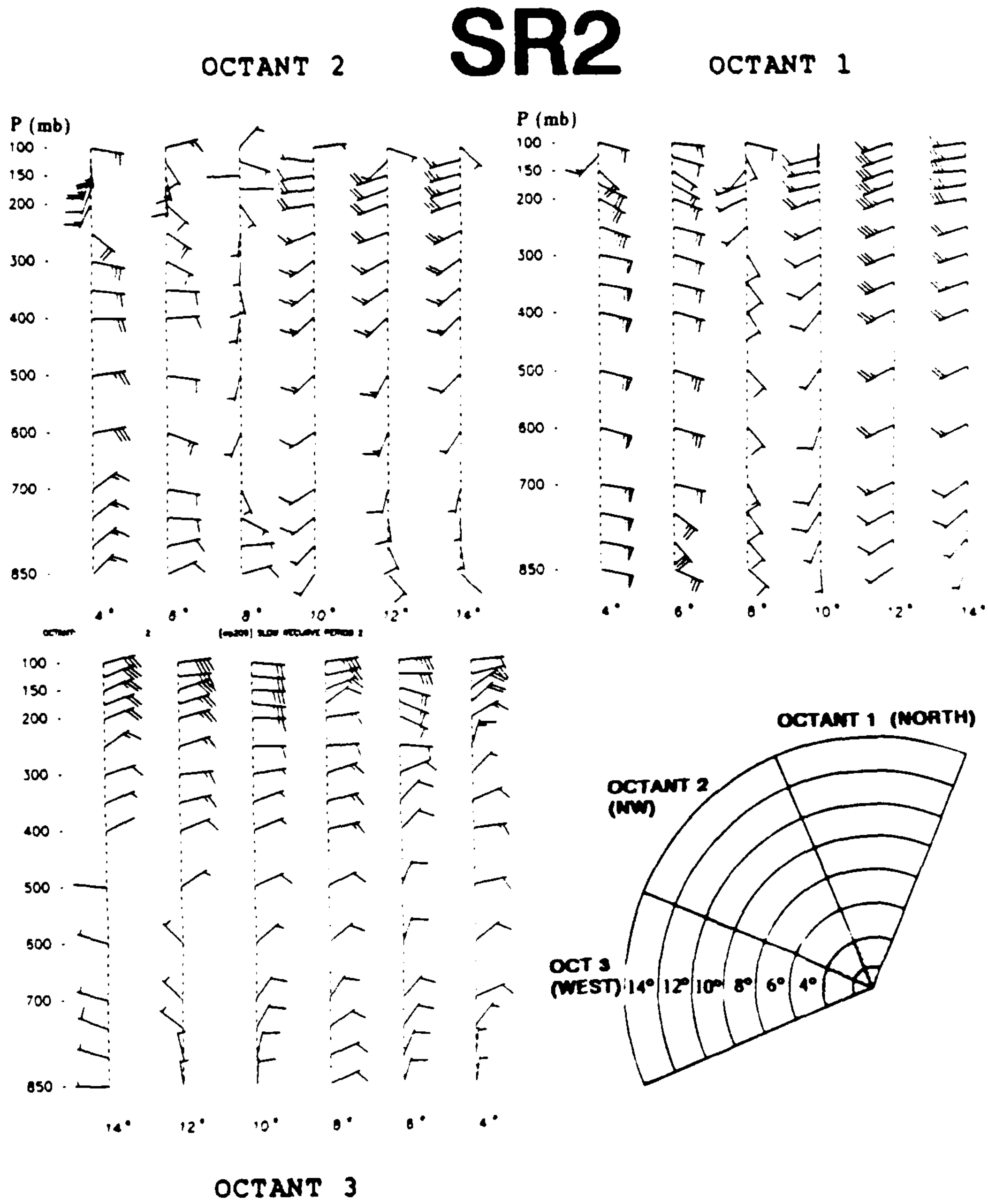

Figure A.5: Same as Fig. A.4 except for slowly recurving cyclones at period SR2.

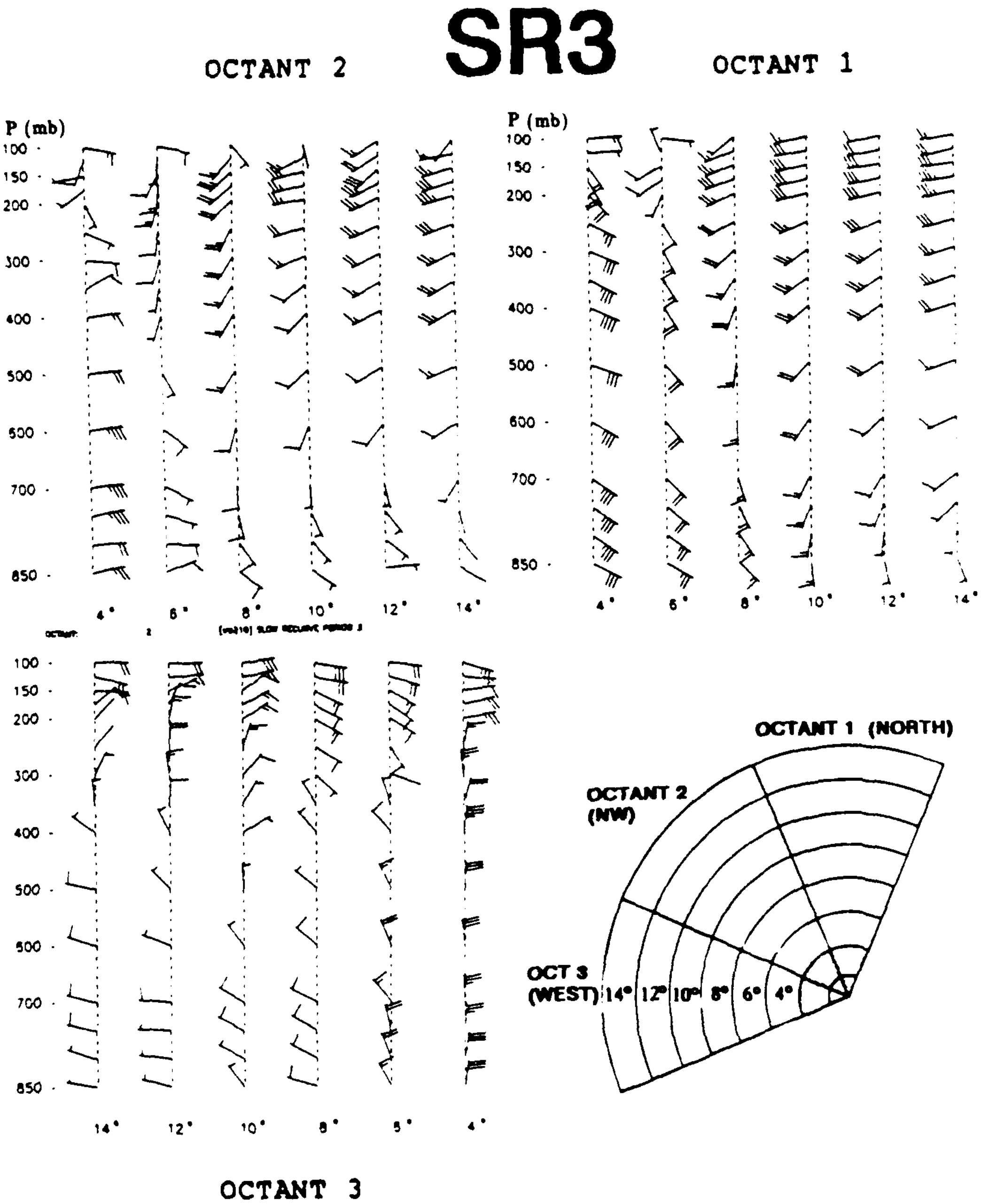

Figure A.6: Same as Fig. A.4 except for slowly recurving cyclones at period SR3.

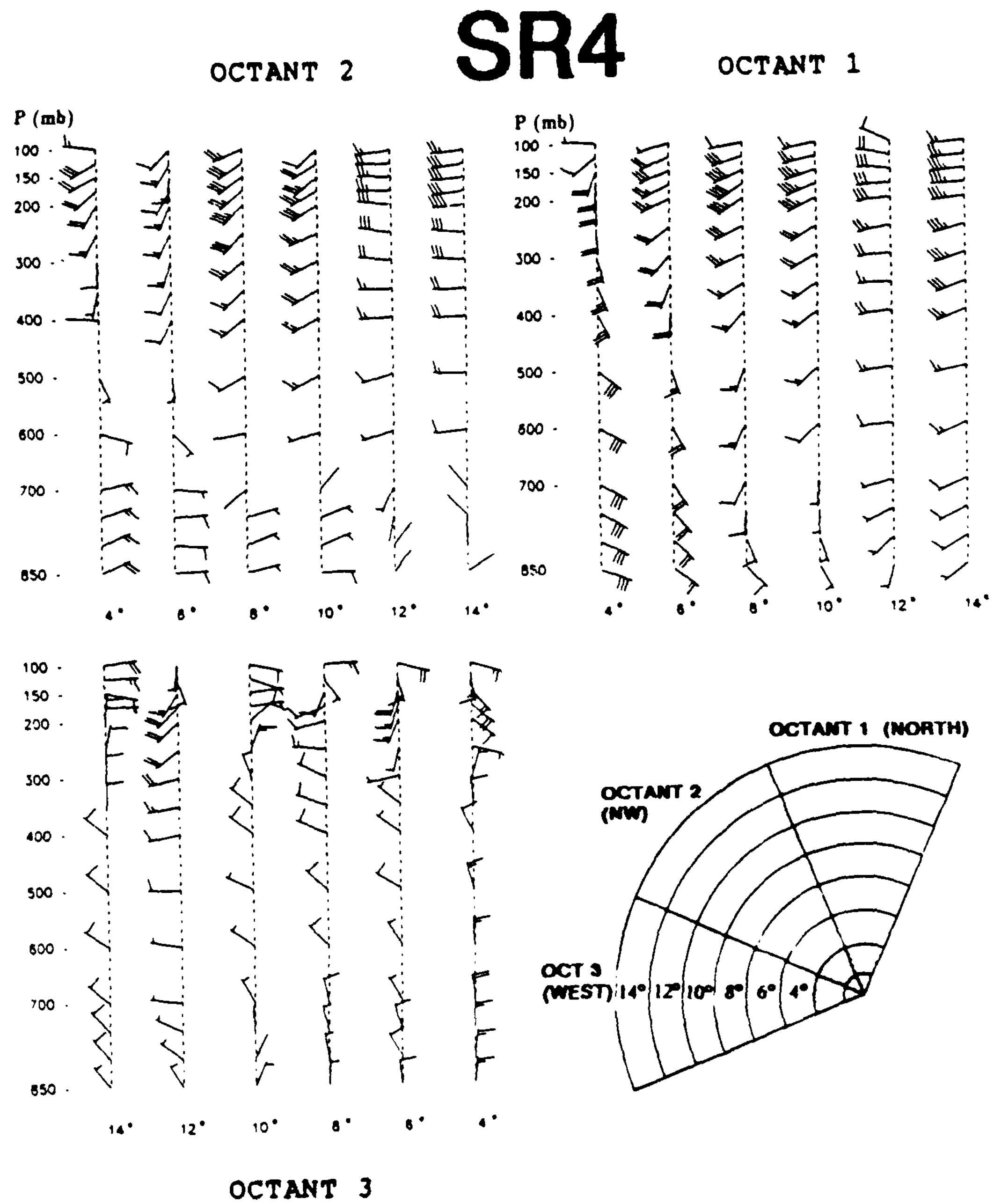

Figure A.7: Same as Fig. A.4 except for slowly recurving cyclones at period SR4.

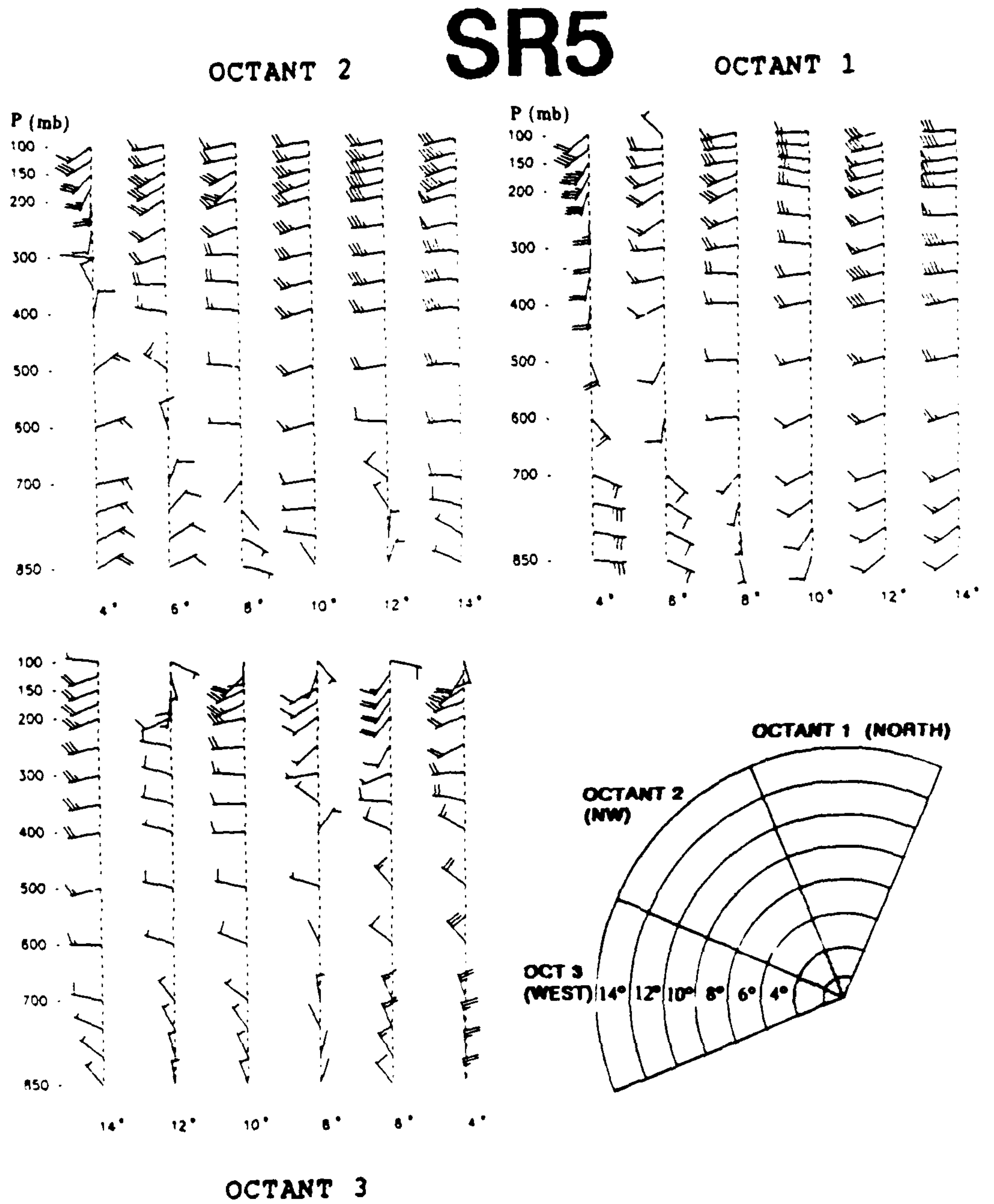

Figure A.8: Same as Fig. A.4 except for slowly recurving cyclones at period SR5.

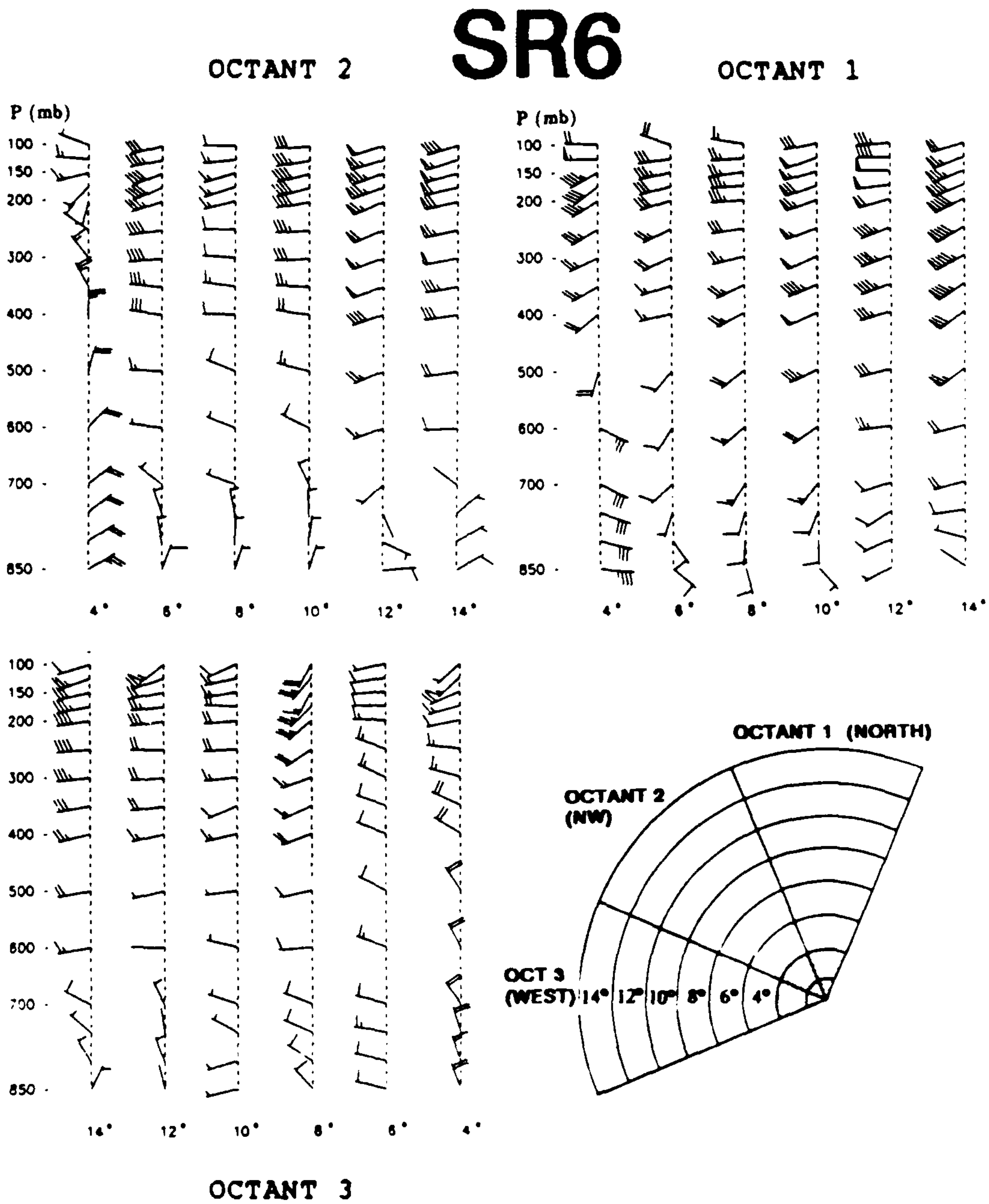

Figure A.9: Same as Fig. A.4 except for slowly recurving cyclones at period SR6.

A.3 Wind Vector Profiles of the Sharply Recurving Cyclones

The wind vector profiles for the 5 sharply recurving cyclone time periods in octants 1, 2 and 3 are shown in Figures A.10 through A.14. At the first time period, Period R0 (Fig. A.10), the winds at 4, 6 and 8° in octants 1 and 2 are predominantly from an easterly component at all levels of the troposphere [9]. Beyond 8°, the wind fields in these two octants shift to a westerly component and increase in speed; winds at 12 and 14° are in excess of 10 to 20 ms^{-1}. The wind fields in octant 3 at this time period are from an easterly direction throughout the troposphere at all radii. At period R1 (Fig. A.11), the zonal winds beyond 8° in octants 1 and 2 have increased in speed, but besides these changes, very little change in the wind fields have occurred at distances closer to the cyclone; the winds at 4, 6 and 8° are still from an easterly component, and the winds in octant 3 are still predominantly from an easterly direction.

Major changes occur to the north and northwest of the cyclone at period R2 (Fig. A.12). Easterly winds which existed 8° from the cyclones' center at period R1 have shifted to westerlies. These westerlies at this radius range from 5 to 10 ms^{-1} in the mid troposphere to 15 to 23 ms^{-1} in the upper troposphere. The westerly winds beyond 8° in octants 1 and 2 range from 25 to 38 ms^{-1}. Although the westerlies have dramatically increased in speed, and have reached to within 8° of the cyclones' center, the cyclones at period R2 are still moving on a west-northwest course. As was emphasized in the main body of the text, the reason why the cyclone did not recurve is the westerlies have not reached to within 6° of the cyclones in octants 1, 2 and 3.

As the cyclones begin to recurve sharply during period R3 (Fig. A.13), the vector wind profiles at this time period show that the westerly winds have penetrated to within 6° of the cyclone in octants 1 and 2. In addition, the deep easterly flow which existed

[9] As was discussed in Section 3.2, the westerlies in the upper troposphere at periods R0, R1, and R2 were believed to be caused by climatology, and were not a precursor of recurvature.

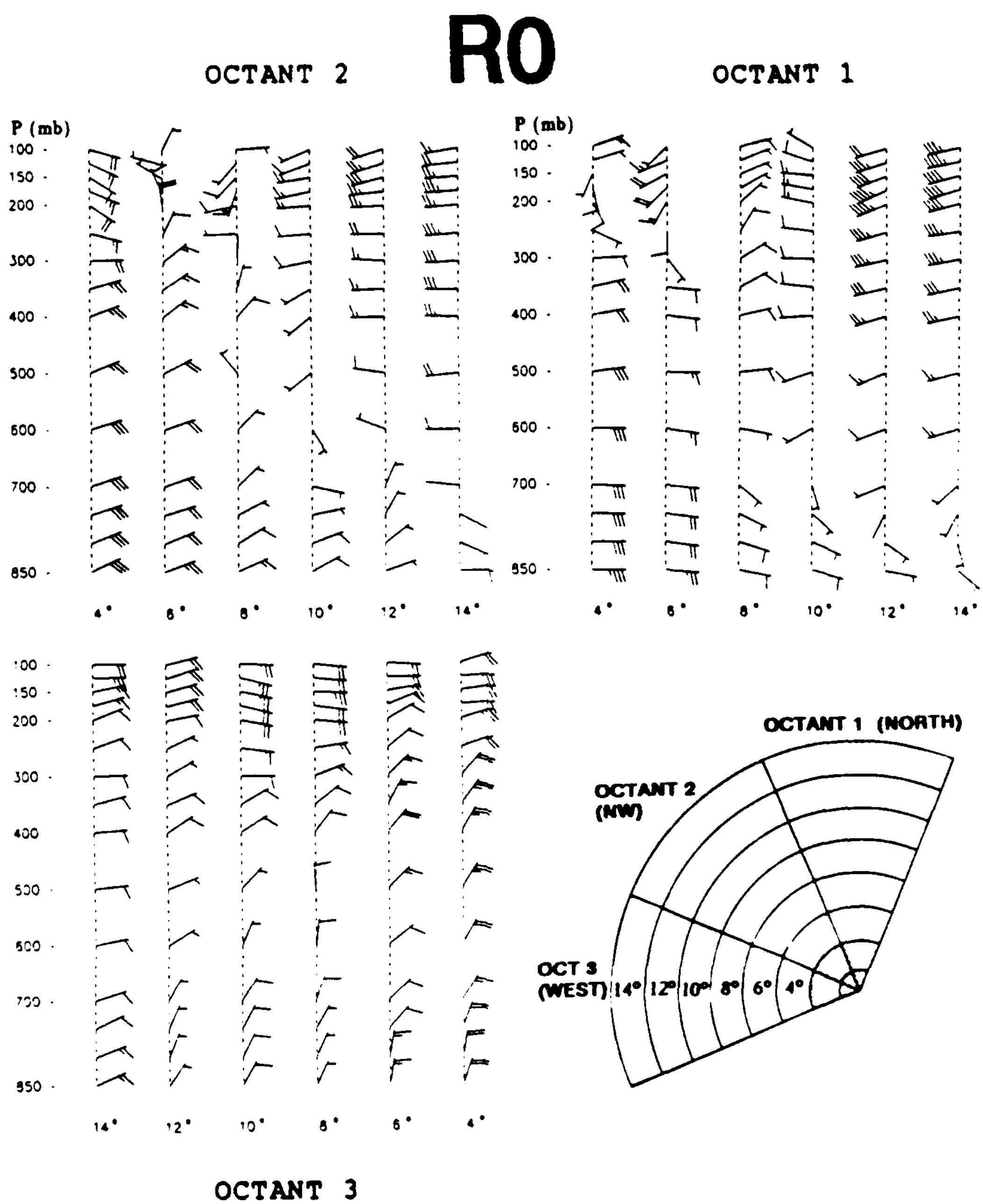

Figure A.10: Wind vector versus radius profiles in octant 1 (top), 2 (upper left) and 3 (left) of the sharp recurving cyclones at period R0. See Figure 2.11 for definition of cyclone time periods.

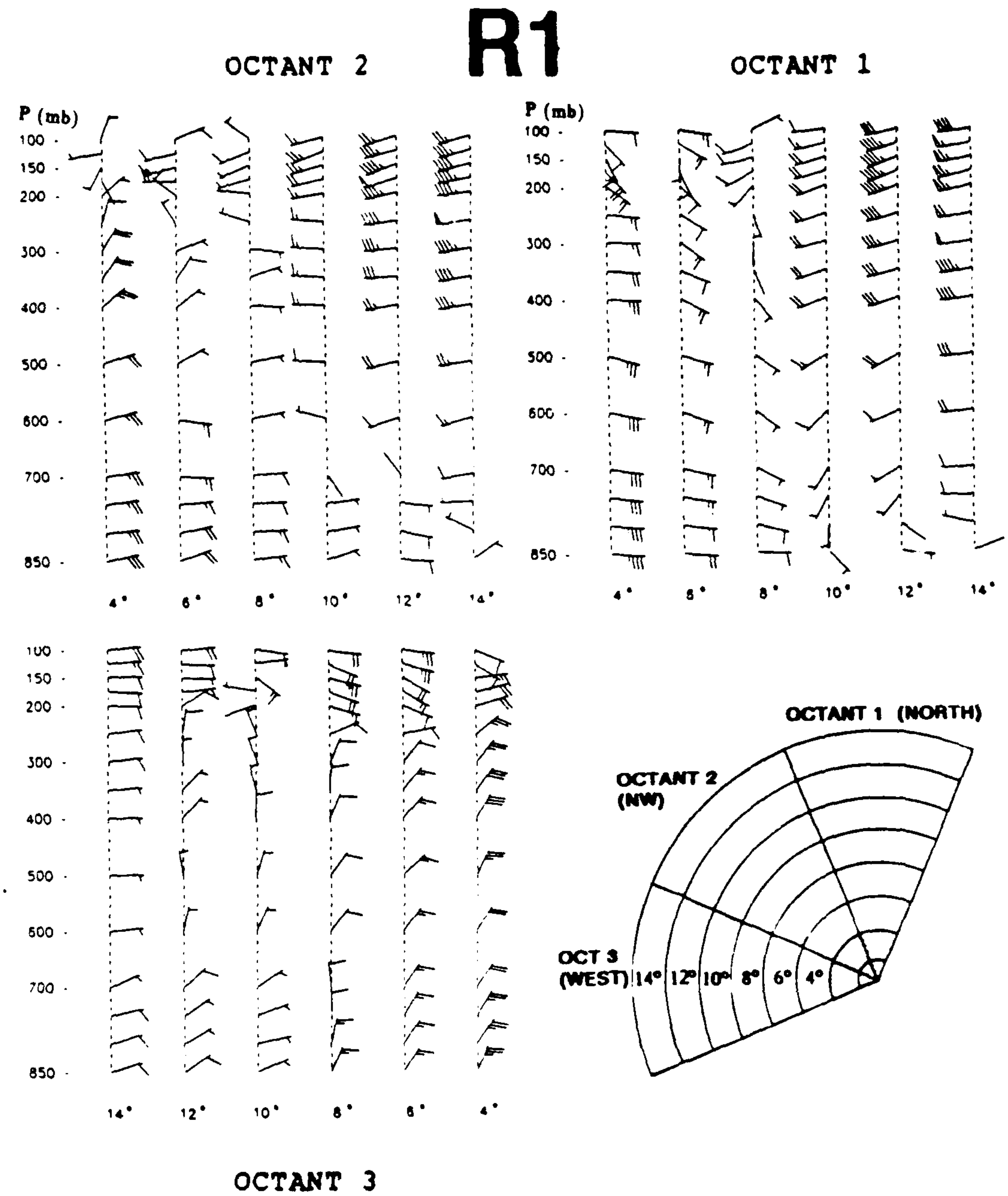

Figure A.11: Same as Fig. A.10 except for sharp recurving cyclones at period R1.

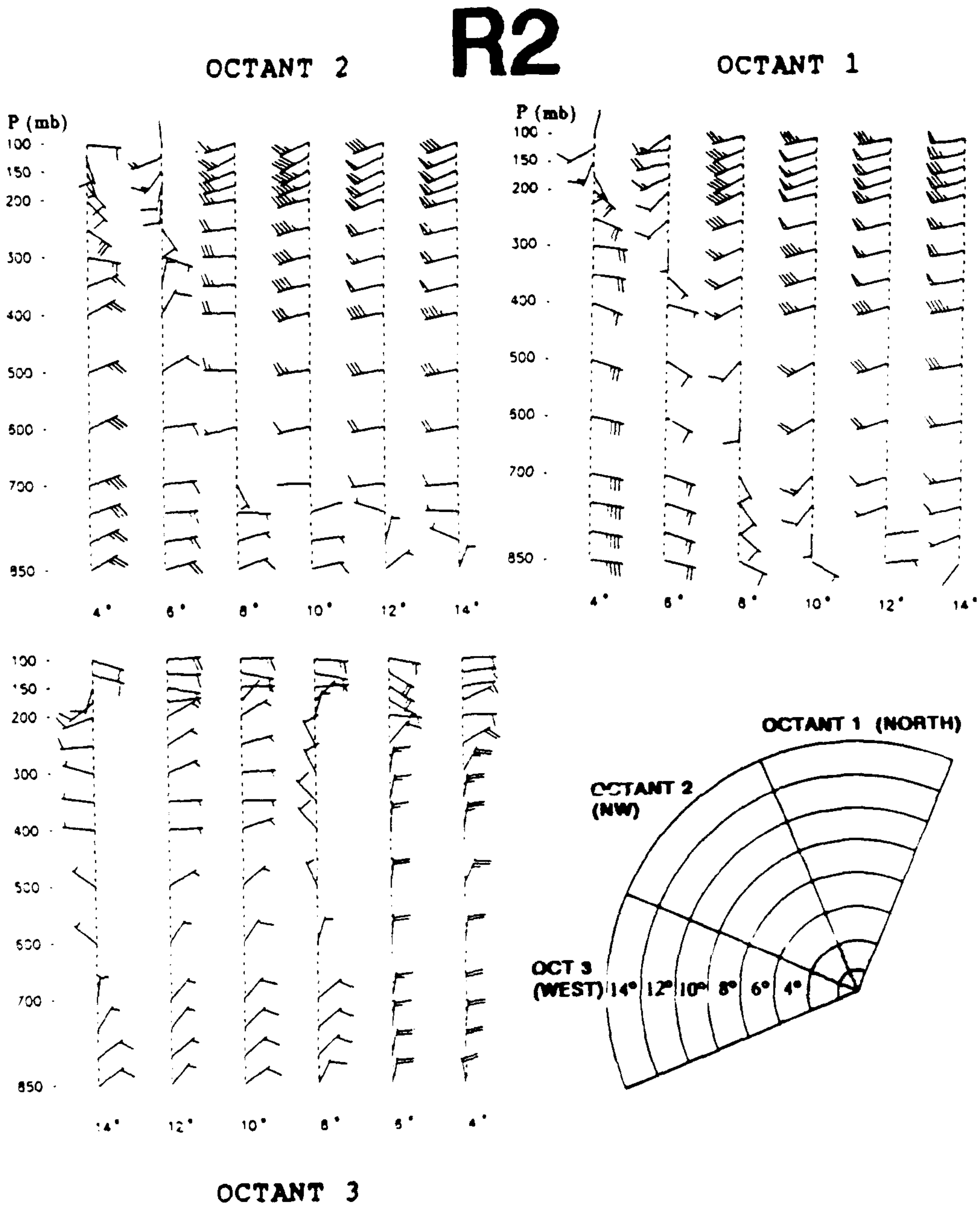

Figure A.12: Same as Fig. A.10 except for sharp recurving cyclones at period R2.

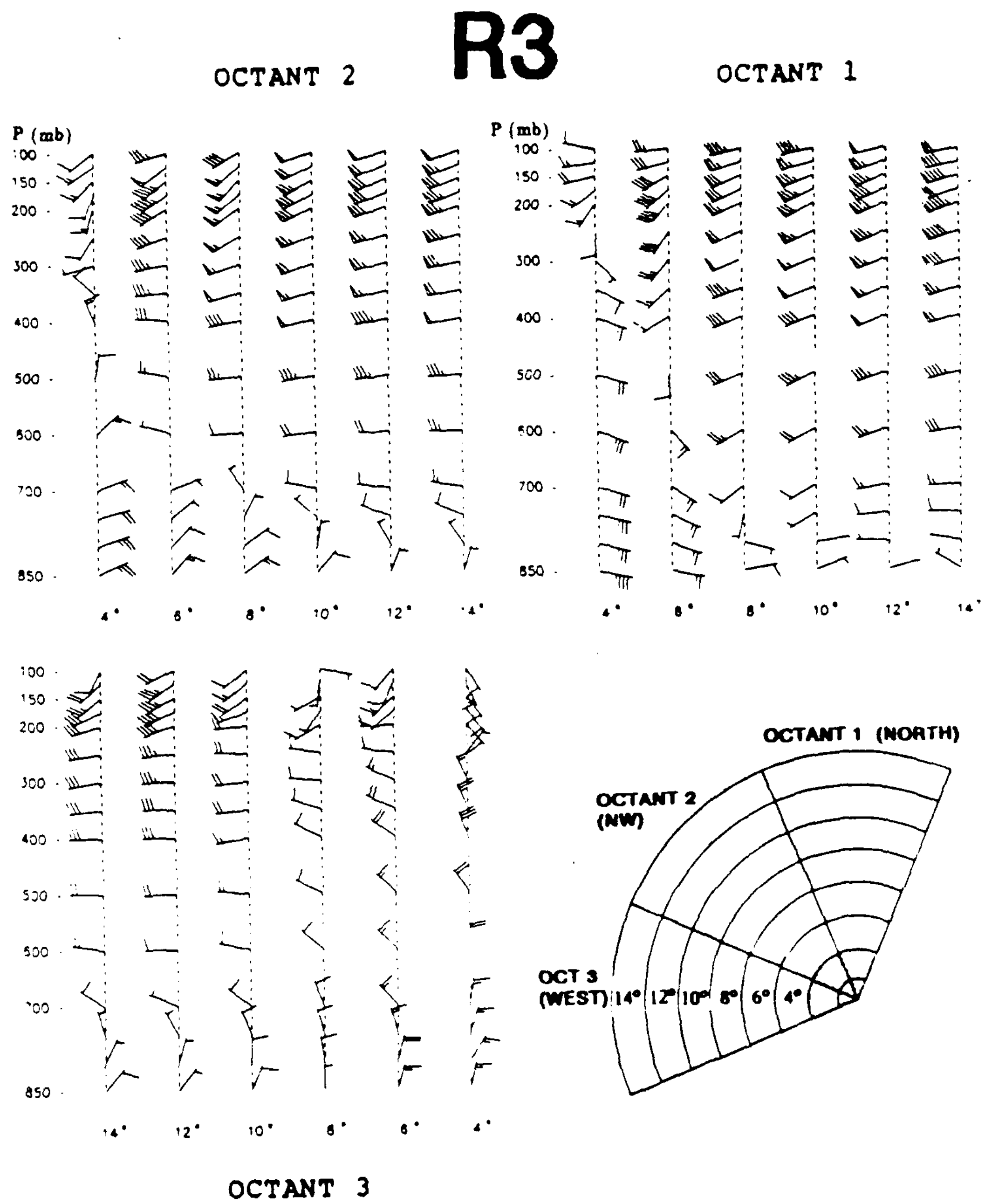

Figure A.13: Same as Fig. A.10 except for sharp recurving cyclones at period R3.

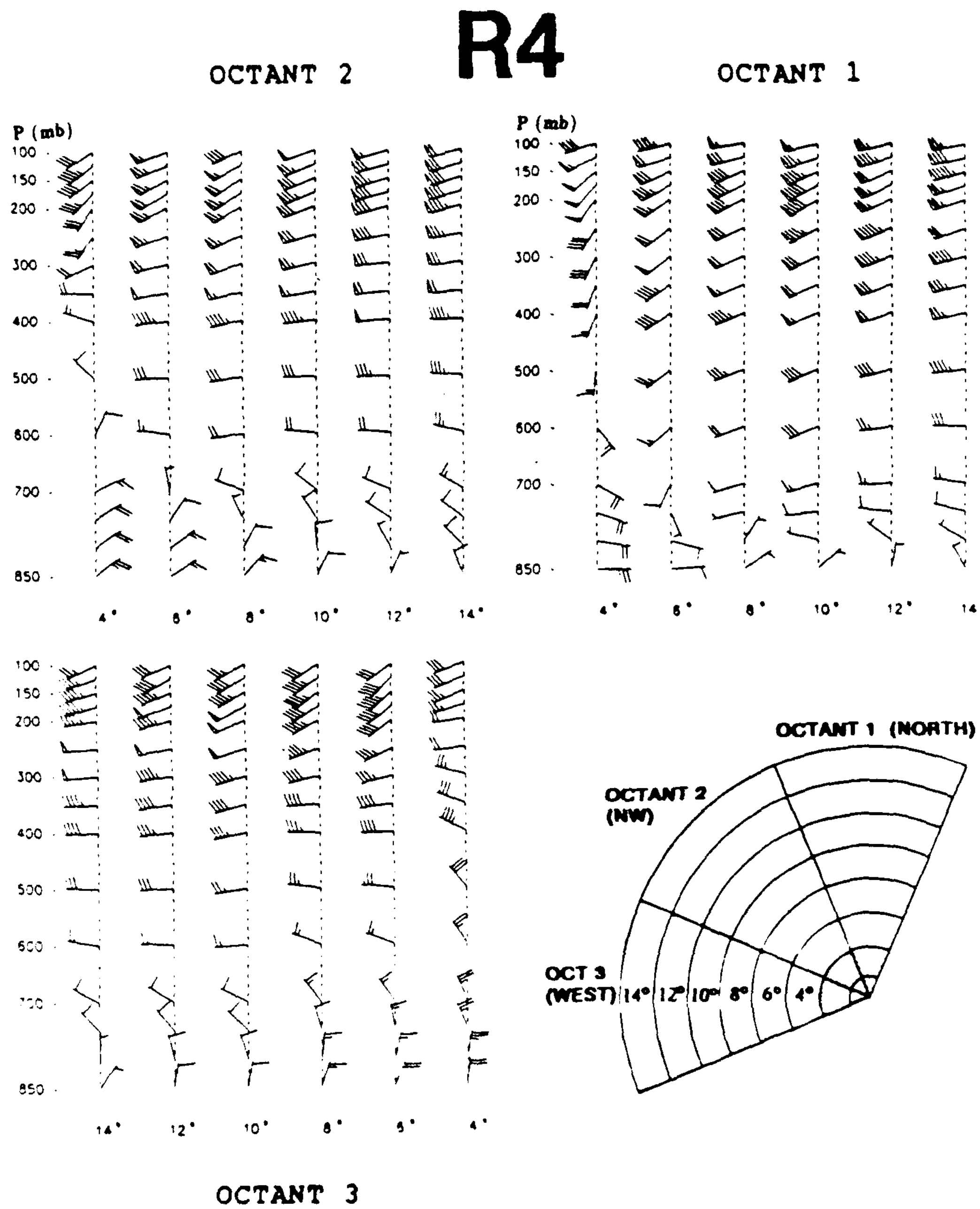

Figure A.14: Same as Fig. A.10 except for sharp recurving cyclones at period R4.

throughout octant 3 at the previous time period has completely shifted to westerlies. As the cyclone accelerate off to the northeast at period R4, the westerlies at all radii and in all three octants increase in speed.

A.4 Wind Vector Profiles for the Left Turning Cyclones

The wind vector profiles for the 4 left turning cyclone time periods in octants 1, 2 and 3 are shown in Figures A.15 and A.17 through A.19. Figure A.15 shows the wind vector profiles for period L3. At this time, anomalous upper tropospheric westerly winds are located at 6 and 8° in octant 1, and at 4, 6 and 8° in octant 3. These westerly winds are "anomalous" for the following reason: If comparisons are made between period L3 and period NR2 of the non-recurving cyclone data set [10] (Fig. A.16), the only significant differences between the two time periods are the upper tropospheric winds at 6 and 8° octant 1, and at 4, 6 and 8° in octant 3.

At period L4 (Fig. A.17), west to south-west winds are still located in the upper troposphere at 6 and 8° in octant 1, but these winds have weakened slightly. The westerly winds in octant 3 meanwhile, have increased in speed and depth, especially at 6°.

Figure A.18 shows the vector wind profiles at period L5. At this time the left turning cyclones have resumed a west-northwest course. However, the westerlies in octants 1 at 8° through 14° have increased in speed. The reason why the cyclones have resumed a west-northwest course is the westerlies, for all practical purposes, no longer exist in octant 3, and the westerlies at 6° in octant 1 have weakened or shifted back to easterlies. At period L6 (Fig. A.19), the westerlies at 6° in octant 1 continue to weaken or shift back to easterlies and the easterlies in octant 3 increase in speed. It is important to notice that the westerlies at 8° and beyond in octants 1 and 2 at this time period have increased in speed,

[10] At period L3, the cyclones were moving slowly to the north-northwest. See Fig. 2.11 for a summary of cyclone directions.

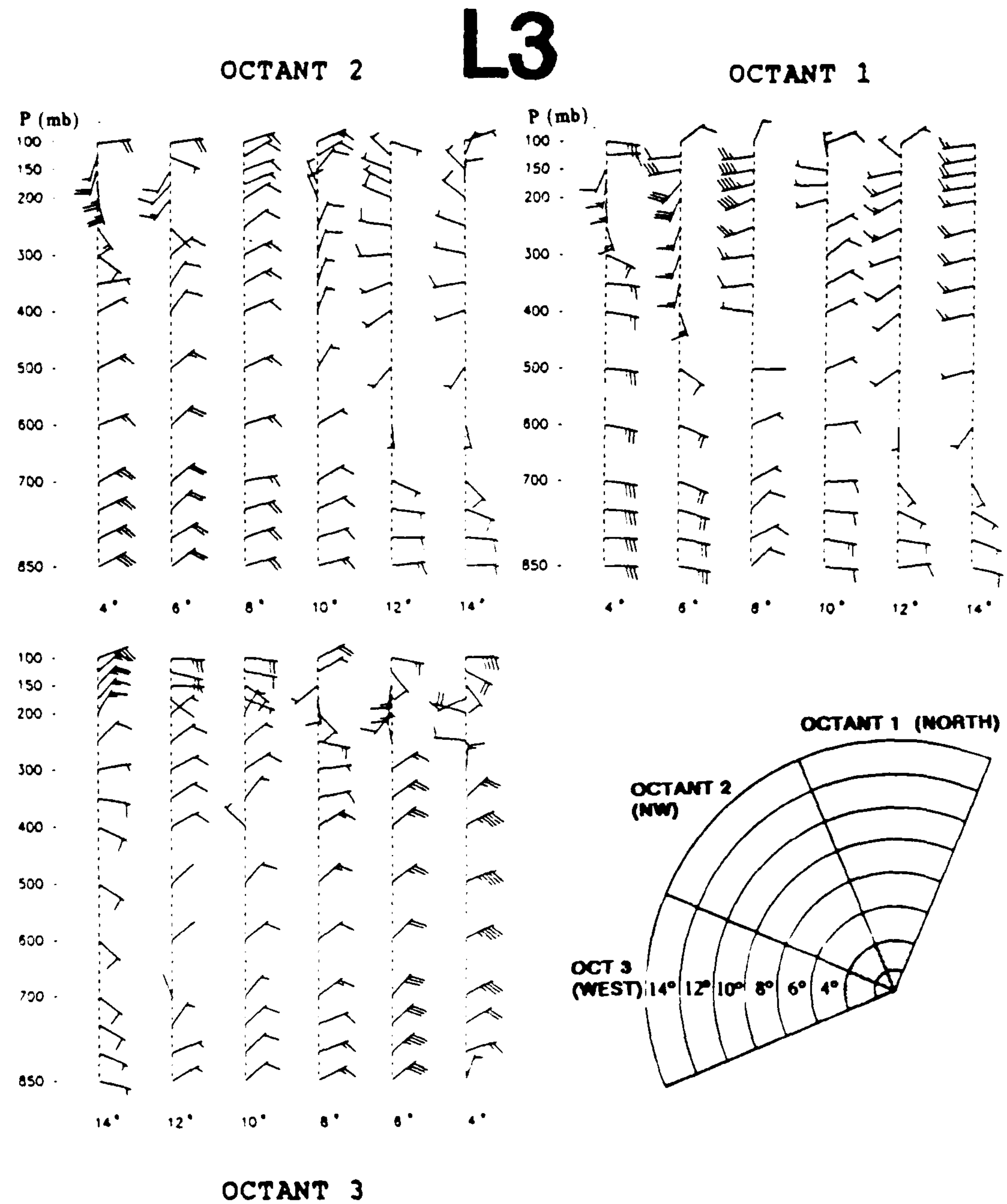

Figure A.15: Wind vector versus radius profiles in octant 1 (top), 2 (upper left) and 3 (left) of the left turning cyclones at period L3. See Figure 2.11 for definition of cyclone time periods.

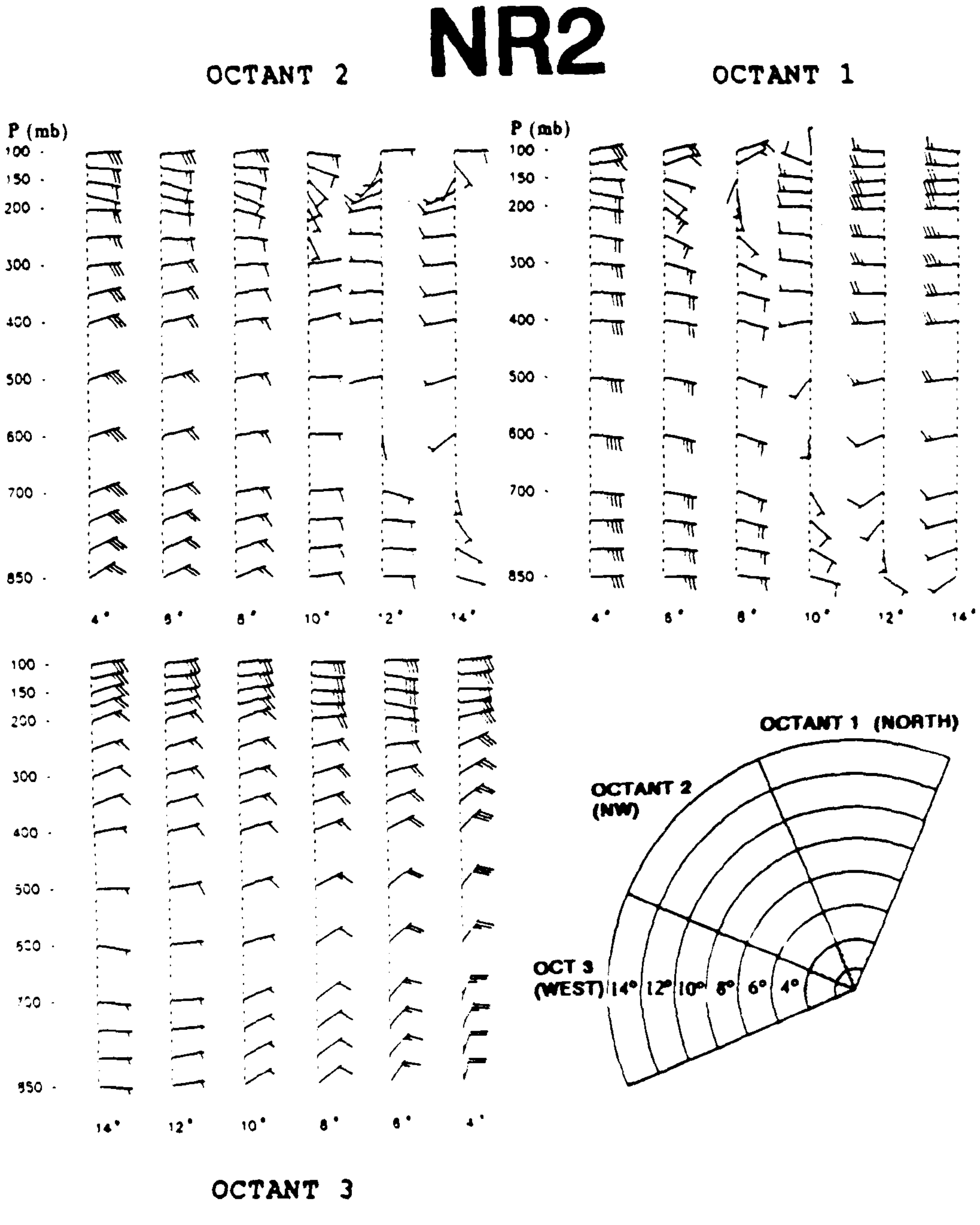

Figure A.16: Wind vector profiles for the non-recurving cyclones at period NR2. The only significant difference between these profiles and the left turning cyclone profiles at period L3 are the wind fields in the upper troposphere at 4, 6, and 8° in octant 1 and 3.

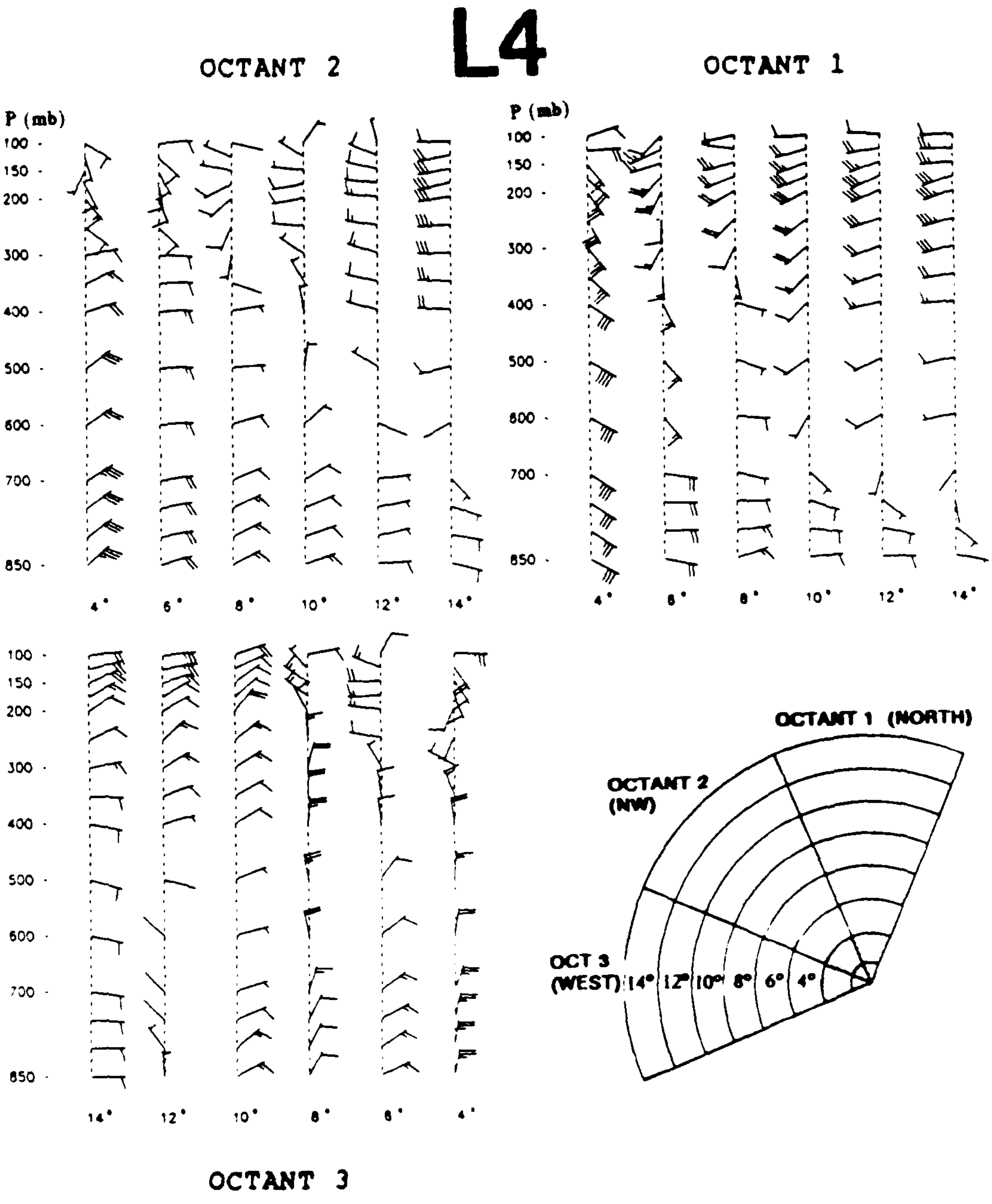

Figure A.17: Same as Fig. A.15 except for left turning cyclones at period L4.

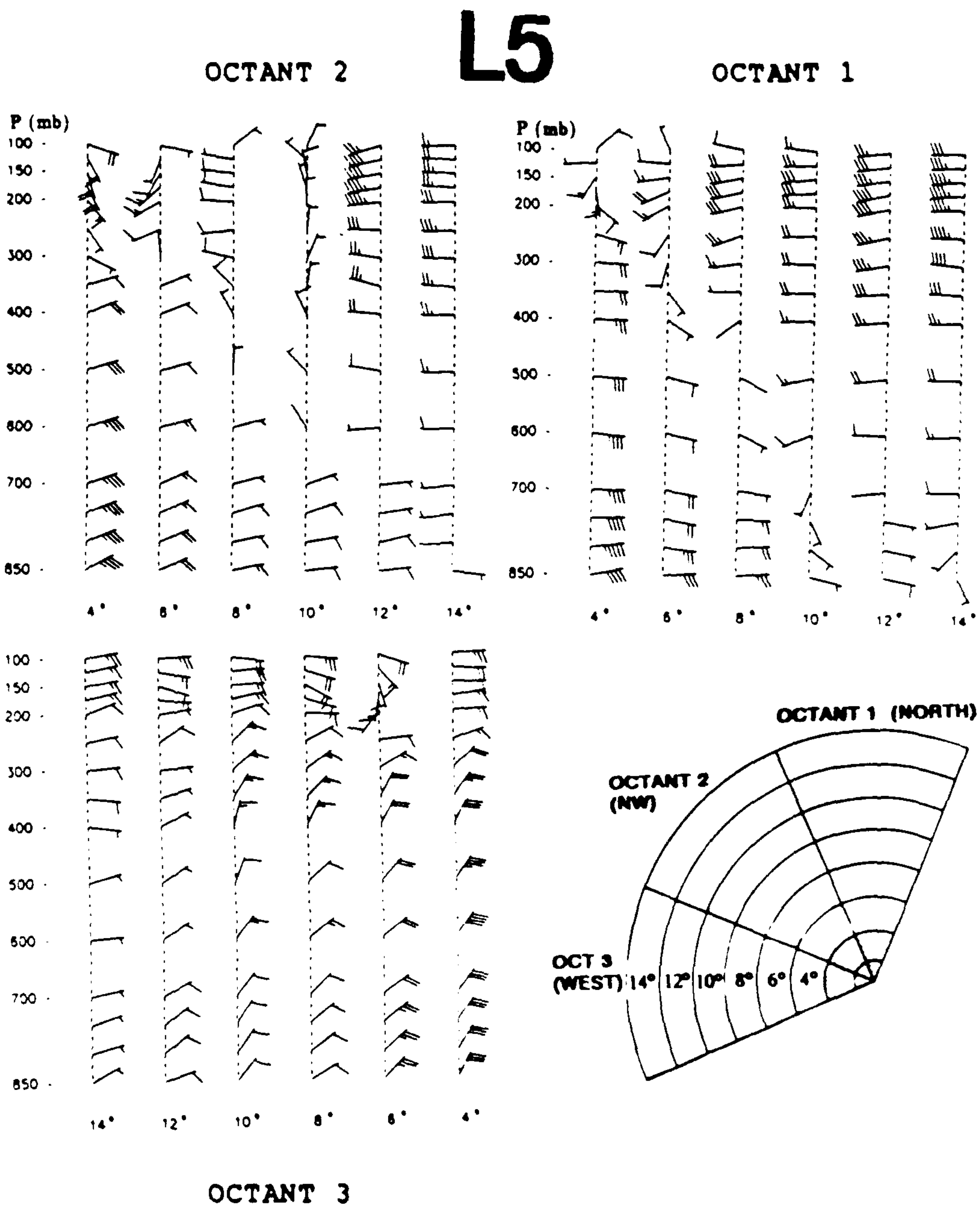

Figure A.18: Same as Fig. A.15 except for left turning cyclones at period L5.

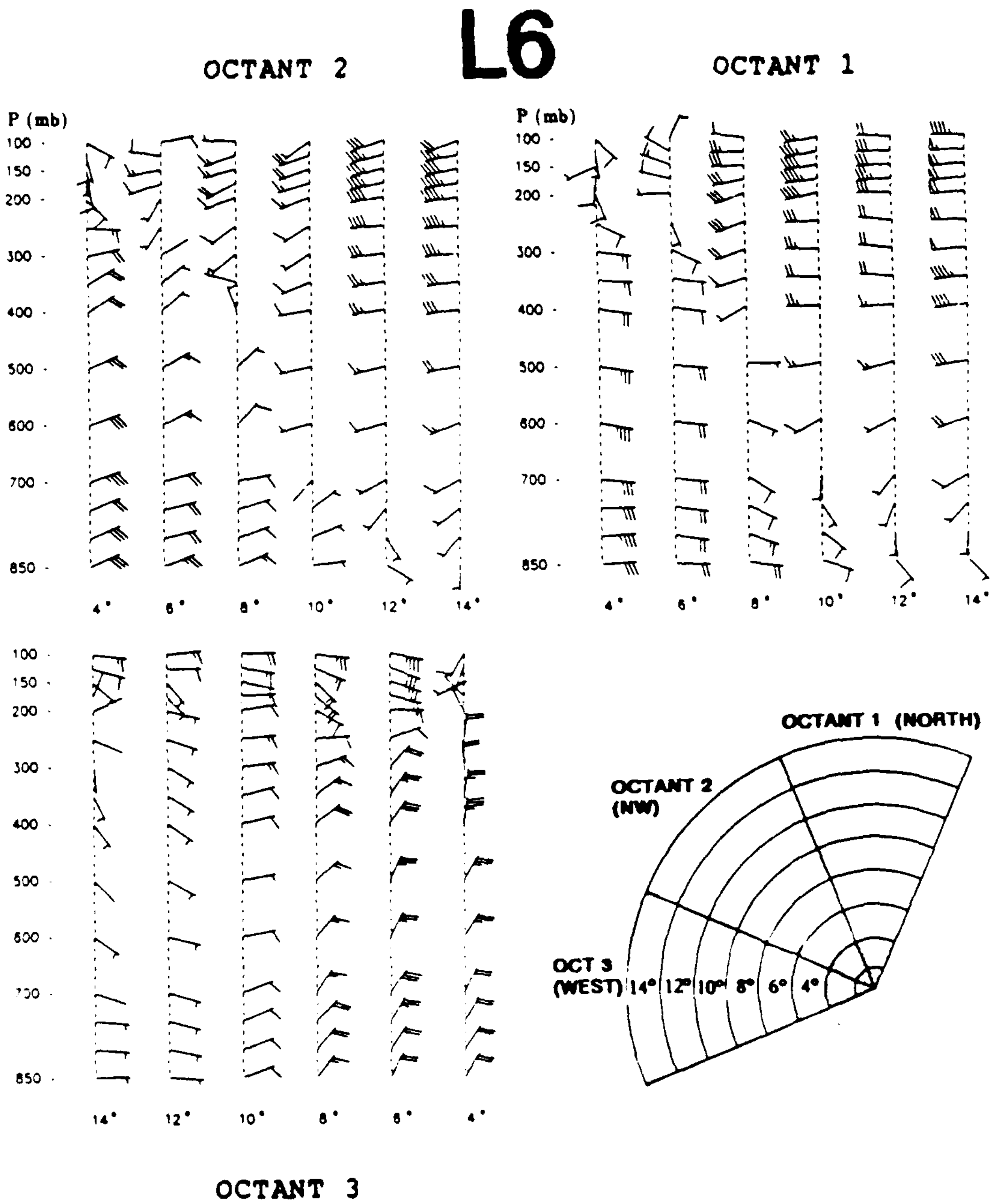

Figure A.19: Same as Fig. A.15 except for left turning cyclones at period L6.

ranging from 15 to 30 ms^{-1}, but the cyclones still continued to move on a west-northwest course.

SUMMARY. The wind vector profiles showed tropical cyclone recurvature is not dependent on the wind fields at 8° and beyond. It was shown tropical cyclones would move on a west-northwest course if the mid and upper tropospheric wind fields 6° to the north, northwest and west of the cyclone were from an easterly component [11]. It was also shown strong westerlies beyond 6° were not necessary for a cyclone to begin recurving. The slowly recurving cyclones began to recurve and the westerlies at 12 and 14° ranged from 10 to 15 ms^{-1}.

[11] As was discussed in Chapter 3, westerly winds in the upper troposphere were found in west-northwest moving cyclones, but these westerlies were usually weak, and did not extend below 300 mbs.

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